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Coastal Benthic Boundary Layer Special Research Program

Program Direction and Workshop Recommendations

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COASTAL BENTHIC BOUNDARY LAYER
SPECIAL RESEARCH PROGRAM

PROGRAM DIRECTION AND WORKSHOP RECOMMENDATIONS

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ABSTRACT

A 5-year Special Research Program (SRP) has been established at the Naval Research Laboratory that addresses the physical characterization and modeling of benthic boundary layer processes and the subsequent impact of these processes on the seafloor properties that affect mine countermeasure operations. This special project outlines the SRP scientific program and reviews the results of the four workshops convened to establish scientific priorities. Workshop participants agreed that sediment structure provides the common perspective: to quantitatively model relationships among sediment-physical properties; to quantify the effects of environmental processes on sediment properties; and to model sediment behavior (acoustic, electrical, and mechanical). Hypotheses based on quantitative physical models that incorporate three-dimensional sediment structure will be tested by a series of field experiments at coastal locations where differing environmental processes dominate sediment structure. These experiments stress the role of sediment structure in determining high-frequency acoustic phenomena such as scattering, penetration, and propagation, as well as the physical relationships between remotely sensed acoustic properties and mechanical strength parameters.

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1.0 INTRODUCTION

Dr. Saalfeld, Director, Office of Naval Research (ONR) requested that the Naval Research Laboratory (NRL) establish a Coastal Warfare Special Research Program (Memorandum 10D/1097, dated 1 July 1991). He cited the lack of basic research emphasis of ONR programs in areas directly related to mine and amphibious warfare and the recent events in the Persian Gulf as justification for the new Special Research Program (SRP). Recent changes in the perceived threats to U.S. security have shifted naval defense scenarios from blue-water, whole-earth conflicts where Antisubmarine Warfare (ASW) reigns supreme to coastal-region, limited-warfare scenarios where mining, mine countermeasures (MCM), and amphibious beach assaults dominate. It is therefore important for research supported by ONR to focus on this new direction.

Dr. Michael D. Richardson was appointed chief scientist of the SRP on August 1, 1991. Management at ONR/NRL established the following guidance for program development. The coastal warfare SRP should address environmental processes that affect MCM and Amphibious Warfare (AMW) operations in coastal waters; should focus on a limited number (1 or 2) of research topics as a result of funding limitations; and should include a mix of the best NRL and university scientists. The chief scientist was to determine the needs of the MCM and AMW communities; assess ongoing basic research programs supporting these needs, both within and outside the Department of Defense (DOD); and draft the outline and structure of a basic research program that would cover outstanding, underaddressed research areas.

Visits to and/or communication with Navy and university research laboratories, program offices, and operational commands (Table 1) were used to determine the needs of the MCM and AMW communities and to assess current research programs addressing those needs. Environmental factors that effect MCM and AMW operations (Fig. 1) include a wide variety of atmospheric, oceanographic, geological, biological, and acoustic properties.

The impact of these environmental factors on MCM and AMW operations can be grouped into the following research categories:

1. Coastal atmospheric and oceanographic conditions affecting ship, ROV, and swimmer handling and safety.

2. Water clarity issues related to remote mine detection and classification (airborne lasers, in-water cameras, and divers).

3. Sediment classification related to mine burial prediction, sediment transport, and acoustic reverberation (buried and proud mine detection and classification).

4. Effects of sea surface and water column characteristics on acoustic propagation and reverberation (detection and classification of floating, moored, and proud mines).

Table 1. Navy and university research laboratories, program offices, and operational commands providing input to MCM and AMW research requirements.

NAVAL STUDIES BOARD, NATIONAL ACADEMY OF SCIENCES
NAVAL COASTAL SYSTEMS CENTER (NCSC)
OFFICE OF NAVAL RESEARCH
ASW ENVIRONMENTAL ACOUSTIC SUPPORT PROGRAM (AEAS)
OFFICE OF NAVAL TECHNOLOGY (ONT)
NAVAL OCEANOGRAPHIC OFFICE (NAVOCEANO)
COMINEWARCOM
TTCP GPT-11
PMA-210
OP-096
PMS-407
ARMY CORPS OF ENGINEERS
SACLANTCEN
FWG (KIEL, GERMANY)
APPLIED PHYSICS LABORATORY (APL) U OF WASHINGTON
APPLIED RESEARCH LABORATORY (ARL) U OF TEXAS
TEXAS A & M
NOAA/SEA GRANT OFFICE
DOE
NSF
USGS
ONR EUROPEAN OFFICE

Atmospheric

- Weather
- Wind speed & direction
- Air temperature
- Ambient light
- Particulate matter
- Sun glint/glare
- Refractive index

Anthropogenic

- Noise
- Obstructions
- Bottom clutter

Hydrography

- Beach slope
- Topography
- Depth range

Oceanographic

- Tides
- Currents
- Surf conditions
- Water temperature
- Salinity/conductivity
- Sea state
- Wave height & direction
- Optical (vertical + horizontal)
- Turbidity
- Bottom pressure
- Ice conditions
- Bubbles
- Absorption (dissolved & particulate matter)

Acoustic

- Scattering & reverberation
- Sound speed profile
- Ambient noise
- Transmission loss

Geophysical/Magnetic

- Bottom roughness
- Bottom type
- Clutter (acoustic & magnetic)
- Sediment conductivity
- Sediment gases
- Geoacoustic properties
- Bottom strength & stability
- Pressure wave transmission
- Ambient magnetic background
- Sediment property gradients

Biologic

- Ambient noise
- Scatterers & False targets
- Bioluminescence
- Reefs, kelp, etc.
- Biofouling
- Hazardous animals
- Optical scattering

Figure 1. Environmental factors which affect MCM and AMW operations.

5. Sediment and water column electromagnetic characteristics (especially conductivity) that affect magnetic influence minesweeping.

6. Characterization of the surf zone processes (sediment dynamics and wave energy distribution) that influence mine detection and clearing operations.

7. Prediction of meteorological, hydrographic, and topographic conditions that adversely affect surf zone and beach landing operations.

8. Sediment characteristics (shear strength, pressure wave attenuation, conductivity) that influence mine operation, mine laying, and mine field planning.

9. Mine burial processes, including impact burial, scour, sand-ridge migration, sediment deposition.

10. Global gradients and local variability of the Earth's magnetic field related to magnetic detection and influence sweeping of mines.

11. Mapping and prediction of water depths and bottom topography related to mechanical minesweeping and determination of magnetic sweep paths.

12. The relative affects of surface waves, internal waves, and ship generated of pressure waves on the operation of pressure influence mines (i.e., ambient noise versus ship's pressure wave signatures).

13. Propagation and attenuation of pressure waves in the water column and sediments relating to sediment-stability issues and ship's wake detection by buried mines.

14. Biological issues as they relate to ambient noise and false acoustic contacts; impediments to mechanical minesweeping, and mine neutralization vehicles (e.g., kelp beds); and diver (e.g., dangerous animals) operations.

Given the extensive lists of MCM and AMW environmental requirements and research categories, it became obvious that only a subset of environmental factors could be addressed by the SRP. Consequently, SRP workshop emphasis was placed on MCM requirements instead of AMW requirements. This choice was not based on weighing and/or comparing MCM and AMW naval requirements because MCM and AMW operations equally need and could benefit from well-directed research programs. This choice was, instead, based on a combination of factors including the strong basic research potential for supporting MCM operations, exploratory and advanced research transition potential, NRL expertise in coastal environmental research, recently established programs supporting AMW issues, and the requirement to establish a coherent, unified program within budget. This choice is supported by the original memorandum establishing the SRP (10D/1097, dated 1 July 1991).

The most pressing problem associated with MCM operations is location and destruction of mines deployed on or within the bottom. Naval objectives of the SRP were therefore

established to improve the performance and performance prediction of MCM systems used to detect, classify, and neutralize mines located within or on the bottom. Specific navy technology issues associated with these MCM systems include acoustic/magnetic detection, classification and neutralization of proud and buried mines; prediction of mine burial at impact and by scour, sand ridge migration, and depositional processes; and development of sediment-classification methodologies required for improved MCM system performance and performance prediction. The basic scientific direction common to all three navy technology issue areas is the physics and modeling of benthic boundary layer processes and the subsequent impact of these processes on seafloor properties that affect MCM operations.

The chief scientist gave the first SRP program briefing to ONR's Scientific Oversight Committee-Executive Council (SOC-EC) on 25 September 1991. The presentation included scientific direction, workshop justification and scheduling, selection of oversight committee members, and tasks and milestones for FY92. General program direction and objectives were approved and will work under the SRP beginning 1 October 1992. Four workshops were convened to prioritize basic research issues addressing both SRP scientific direction and specific naval technology issues. Workshop recommendations are summarized in the next section.

2.0 WORKSHOPS

The workshop participants were chosen, and meetings were conducted by local chairpersons (experts in their fields) with little or no interference from ONR/NRL. Chairpersons were also responsible for documenting workshop results and recommendations. Participants and chairmen are to be commended for their excellent suggestions, enthusiasm, and dedication. All workshops followed the same basic format. The workshops began with a summary of the SRP objectives and a statement of scientific issues to be addressed. Workshop participants were given time to present their current research programs (posturing) or review overall research direction in their field of expertise. Brainstorming (all ideas presented) followed by consensus building (prioritizing issues and developing possible solutions) occurred both in subgroups and with all members present. The outlines of a workshop report were generated at the end of each meeting. The results and recommendations of individual workshops are presented in Appendices A-D.

2.1 SEABED-STRUCTURE INTERACTION

The seabed-structure interaction workshop was held in Metairie, LA, on 5-6 November 1991, chaired by Drs. Richard Bennett (NRL), Wayne Dunlap (Offshore Technology Research Center) and Homa Lee (USGS). The workshop was convened to address dynamic, time-dependent processes affecting objects coupled with the seafloor. Naval interest includes mine burial by impact and subsequent burial by scour, sand ridge migration, and depositional processes. Current mine burial models used by the Navy lack time dependence and are based on mostly empirical as opposed to physical relationships.

It was noted by Dr. Richard Bennett and others that objects coupled with the seafloor constitute a "dynamic system" and modeling must include: (1) environmental forcing of the

object and the seabed; (2) fundamental properties of the geological material, including time-dependent changes; (3) size and shape of the object; (4) time-dependent processes associated with the coupling of water column, seabed and the object; (5) scales ranging from microns to meters; and (6) saturated and unsaturated sands, silts, clays, and admixtures of those sediment types.

The seabed-structure interaction workshop addressed two important technical areas: (1) Sediment Transport: Scour and Fill; and (2) Geotechnical: Seabed Interactions. The ultimate goal of research in the area of "Sediment Transport: Scour and Fill" is development of physical models that describe wave/current interactions with the seafloor, both with and without the presence of a mine-like object. Specific research issues, which support MCM operations, include an understanding of: (1) scaling effects and scaling laws that are required to interpret laboratory and field scour and fill experiments; (2) nonlinear wave-current and turbulent hydrodynamic variations induced by the presence of an object in the flow field; (3) the role of dynamic pore pressure on sediment stability around a solid body coupled with the seafloor under different frequency wave-current conditions; and (4) the role of fine-grained sediment microstructure (both fabric and physiochemistry) on scour and fill processes.

Research in the area of "Geotechnical: Seabed Interactions" should lead to improved stress/strain models among objects, sediments, forcing functions, and environmental factors (e.g., hydrodynamic stress). Specific research objectives include an understanding of: (1) the importance and influence of permeability, sediment type, and microfabric on the development of excess pore pressure in sediments and degradation of sediment strength under dynamic loading conditions with an object coupled to the seabed; (2) attenuation of wave induced pore pressure as a function sediment type, depth and wave climate; (3) wave induced sediment deformation, stresses (total and pore pressure), and sediment coupling of objects in dynamic motion on the seafloor; and (4) the role of gassy sediment in the dynamic behavior of object-sediment coupling.

2.2 RELATIONSHIPS BETWEEN ENVIRONMENTAL PROCESSES AND HIGH FREQUENCY ACOUSTIC SCATTERING/PROPAGATION PHENOMENA AT THE BENTHIC BOUNDARY LAYER

The interaction between environmental processes and the high-frequency acoustics workshop, chaired by Drs. Darrell Jackson (Applied Physics Laboratory, University of Washington) and Peter Jumars (Oceanography Department, University of Washington), was held in Seattle, Washington, on 5-6 December 1991. Current high-frequency acoustic mine detection and classification systems (operating between 10 kHz and 700 kHz) are limited by both bottom reverberation and bottom penetration, making buried mine detection very difficult. Considerable improvement in high-frequency acoustic system performance and performance prediction is therefore possible. Scientific issues addressed by the workshop included an understanding of physical processes and models that predict acoustic scattering, penetration, and propagation phenomena at a heterogeneous poroelastic benthic boundary layer and the deterministic and stochastic relationships between these acoustic phenomena and hydrodynamic, biological, physical, biochemical, and geochemical processes.

The workshop participants recognized the need for research on a hierarchy of high-frequency, acoustic, bottom interaction models. This hierarchy includes acoustic models that predict propagation and scattering based on sediment composition; state models of sediment-physical properties that integrate sediment physical, structural, electrical, rheological, and geoacoustic properties; and environmental models that describe the effects of hydrodynamic, biological, and chemical processes on sediment structure. Current acoustic theory has not been able to adequately predict high-frequency scattering, absorption and propagation phenomena at the seafloor because: (1) the level of environmental complexity found in nature has not been incorporated into acoustic scattering and propagation models; (2) sediment-physical properties are not routinely measured at scales required to predict high-frequency acoustic phenomena; and (3) environmental controls of acoustically relevant physical properties are not adequately documented or modeled.

Workshop participants endorsed a "team approach" including both laboratory tank and field experiments to address the aforementioned acoustic research issues. Experiments should include acoustic transmitters and receivers both in the water column and in sediments in order to separate acoustic propagation and scattering phenomena at the sediment-water interface from those in the sediment volume. Sediments should be treated and modeled as a heterogeneous poroelastic medium, and acoustic waves in this medium should be measured using three-axis accelerometers. Techniques need to be developed to measure three-dimensional sediment structure at scales of microns to meters.

Laboratory and field research should address the following high priority environmental/acoustic issues: (1) scattering from sediment-volume lateral heterogeneities verses boundaries; (2) existence and importance of alternate propagation modes (shear waves, interface waves, and compressional waves of the second kind); (3) mode transformations at boundaries and internal heterogeneities; (4) mechanisms controlling depth of acoustic propagation into the bottom including attenuation and ducting by burrows and tubes; (5) effects of biochemical and geochemical binding on sediment bulk and shear moduli; (6) production of gas bubbles and subsequent effects on acoustic scattering and attenuation; (7) time-rate changes in sediment microtopography related to biological and physical processes; and (8) fractal verses nonfractal representation of sediment microstructure and microtopography.

2.3 DEVELOPMENT OF SEDIMENT-CLASSIFICATION METHODOLOGIES REQUIRED FOR IMPROVED MCM SYSTEM PERFORMANCE AND PERFORMANCE PREDICTION

The sediment-classification workshop was held in Austin, Texas on 5-6 February and was chaired by Drs. Tom Muir (Applied Research Laboratory, University of Texas) and Clarence Clay (University of Wisconsin). Sediment classification (e.g., sediment type, grain size, shear strength) provides required input to many MCM operational system performance prediction models. This research should, therefore, provide the "bridge" between environmental processes and MCM operational requirements. Specific scientific issues addressed at the workshop included: (1) nonlinear acoustic interactions with a heterogeneous bottom and subbottom; (2) development of pattern recognition techniques, based on physical principles,

for rapid, reliable sediment classification; and (3) the use of sediment classification as a tool to characterize environmental processes that create or modify near shore sediments.

Workshop participants agreed that no universally acceptable definition of sediment classification exists. It was suggested that a matrix of remotely sensed properties, together with in situ measured mechanical, acoustic and electrical properties, should be subjected to factor analysis. Natural clusters could form the basis for sediment classification with factor axes representing controlling environmental processes.

Current relationships between sediment-bulk properties (porosity, grain size, density, permeability), mechanical properties (shear strength, compressibility), geoacoustic properties (compressional and shear wave velocity and attenuation), and electrical properties (conductivity) are based primarily on empirical or quasi-physical models. Theoretical relationships among these properties may be tied to more "primitive" type parameters such as those that describe energy propagation through a fluid-filled porous medium (fluid density, compressibility, and viscosity; pore size; tortuosity; porosity; permeability; and elastic complex frame bulk and shear moduli). Verification of current theoretical relationships (e.g., Biot Model) or development of new, more universal models incorporating a three-phase (gas, water, and solids), heterogeneous medium are required to develop physical relationship between remotely sensed and operationally required parameters.

Workshop participants divided specific research objectives into those relating to theoretical, experimental, and measurement aspects of sediment classification. Most of these scientific issues can be grouped into theoretical or empirical relationships among sediment parameters; the behavioral response of sediments to acoustic, mechanical, and electrical stress; and methods to characterize sediment-acoustic response. All groups stressed the ability to remotely measure or predict undrained sediment-shear strength. The need to measure, understand, and statistically characterize the spatial (three-dimensional) and temporal distribution of sediment properties also was emphasized. Issues related to theoretical prediction of high-frequency acoustic scattering, penetration, and propagation phenomena near the sediment-water interface received considerable attention at this workshop, especially the relative contributions of surface roughness and sediment-volume heterogeneity to acoustic scattering. These acoustic issues overlapped with the recommendations of the high-frequency acoustic interaction and seabed-structure interaction workshops.

2.4 ENVIRONMENTAL PROCESSES RESPONSIBLE FOR FINE SCALE ELECTRO-OPTIC VARIABILITY IN THE COASTAL ZONE

The electro-optic and electromagnetic workshop was held in Washington, DC on 10-11 March 1992 with Dr. Gary Gilbert (ONR) as chairperson. Originally, this workshop was called to examine the effects of benthic boundary layer processes on the distribution and variability of sediment electromagnetic (conductivity and natural magnetism) and electro-optic (near-bottom water clarity, optical scattering from the seafloor) properties. The scope of the workshop was expanded to include the full range of coastal optic and electromagnetic issues in order to develop research priorities for all ONR programs.

Workshop participants concentrated on electro-optic rather than electromagnetic issues. This section therefore concentrates on electro-optics with electromagnetic issues summarized in section 2.5.

Ocean optics scientific issues can be divided into those primarily driven by the physics of optical transmission and those related to the environmental processes that control either the distribution of dissolved and particulate material (absorption and scattering) or processes that affect boundary conditions (scattering from the air-sea or water-sediment interfaces).

Ocean optical properties include inherent optical properties (IOPs) such as absorption, scattering, and attenuation that exist regardless of radiance or other environmental conditions and apparent optical properties (AOPs) that are measured, given specific ambient conditions such as ocean color and radiance attenuation (e.g., Secchi disk depth). Optical remote sensing techniques (satellite and airborne color scanners) can measure AOPs. For the Navy and the ocean optics community, understanding the relationships between IOPs and AOPs is central to future research.

The ocean optics community has conveniently divided ocean waters into two types. The optical properties of Case I (offshore, blue water) waters are dominated by the biological processes that control the distribution of phytoplankton chlorophyll. Ocean color and optical attenuation (after absorption and scattering of seawater is accounted for) is controlled primarily by chlorophyll absorption and secondarily by scattering from plankton. AOPs are easily measured and predicted in Case 1 waters. The optical properties of Case II (inshore, brown water) waters are controlled by a much more complex interaction of biological, geological, and oceanographic processes. Ocean color and attenuation result from absorption by organic (e.g., chlorophyll and terrestrial decay products called gelbstoff) and scattering from suspended particulate material (biological and terrestrial sources).

The optics community suggests future research focus on both Case II waters and the transition between Case I and II waters. The major research issues can be divided into the following topical areas:

1. Radiative Transfer in Case II waters (development of inversion algorithms to determine IOPs from AOPs; closure in Case II waters, i.e., verification of attenuation = scattering + absorption relationships; spatial and temporal scales of ocean optical properties; and the influence of coastal boundary conditions on IOPs and AOPs).

2. Relationship of inherent optical properties and properties of dissolved and suspended material (scattering and absorption from suspended particulate matter; absorption by dissolved gelbstoff or yellow matter; and the use of optical techniques to determine the concentration and nature of dissolved materials).

3. Spatial and temporal distribution of IOPs as related to physical, biological, chemical, and geological oceanographic processes (including the sources, sinks, and processes governing both the evolution and the spatial and temporal distribution of yellow matter and suspended particulate matter).

4. Development of instrumentation and techniques for Case II waters (the dynamic range, temporal, spatial, spectral scales of optical properties are different than in blue waters).

It is obvious from workshop discussions and the final workshop report that coastal optical, physical oceanographic, biological, geological, and chemical processes are highly interrelated and study of coastal optical properties in isolation would be fruitless. These interrelationships and recommendations for additional interdisciplinary research are presented in Appendix D.

Optical research issues that best overlap with the objectives of the Benthic Boundary Layer SRP include: (1) generation and maintenance of near bottom nepheloid layers; (2) development of optical measurement technology for determination of size and distribution of suspended particulate matter that is required for benthic boundary layer sediment-dynamics studies; (3) optical diagnostic characterization of sediment microstructure; and (4) bottom spectral reflectance (natural visible or blue-green laser) as a method of sediment classification or mine field detection.

2.5 ELECTROMAGNETIC VARIABILITY IN COASTAL MARINE SEDIMENTS

Electromagnetic issues were not extensively discussed at the EO/EM workshop; however, they were briefly covered at all four workshops. Dr. Ed Mozley has provided a summary of all those discussions (Appendix E). This document focuses on processes responsible for the spatial and temporal gradients, fluctuations, and variability of electrical conductivity in coastal marine sediments. Sediment conductivity controls sediment electrical depth, an important input parameter for magnetic minesweeping performance prediction. Appendix E focuses on electromagnetic issues relevant to MCM operations and is meant to compliment the more comprehensive review on coastal electromagnetic issues (SIO Reference 90-20, April 1991).

Basic research issues include the following:

1. Quantification and modeling of the affects of environmental processes on sediment conductivity. Dominant environmental processes include erosional and depositional events, bioturbation, biogeochemical processes that affect pore water and frame conductivity, fresh water intrusions, and gas bubble generation.

2. Understanding and modeling of the fundamental relationships among sediment conductivity and porosity/permeability and sediment microstructure.

3. Quantification of spatial and temporal variability of sediment conductivity with an emphasis of relationships between conductivity derived from large scale mapping techniques and fine scale in situ measurement techniques.

4. Physical relationships between sediment conductivity and sediment-acoustic behavior.

5. Inversion of sediment conductivity and microscopic sediment structure from macroscale remote geophysical measurements.

3.0 COMMON THREADS

All workshop reports stress the importance of understanding the effect of environmental processes on sediment physical, geoacoustic, rheological, and electrical properties. Some of the important environmental processes are bioturbation, biochemical reactions related the organic matter oxidation, geochemical reactions related to pore-water chemistry and permeability, wave-current hydrodynamic stresses at the sediment-water interface, and processes responsible for gas formation. Equally important is understanding the effects of stress conditions, including consolidation history and pore pressure variations on sediment properties. Most models relating environmental processes to sediment properties are either anecdotal or empirical. Models based on physical principles must be developed if we are to quantitatively predict sediment-physical properties from our knowledge of environmental processes.

Relationships among various sediment-physical, rheological, geoacoustic, and electromagnetic properties need to be quantified. Remotely sensed acoustical, electrical, and optical properties must be quantitatively related in situ sediment-physical properties. The general consensus was that current empirical relationships among sediment properties are inadequate and often misleading. Recently developed or proposed models await adequate experimental verification.

Heterogeneity is the rule not the exception with respect to sediment-property spatial (microns to kilometers) and temporal (microseconds to years) distributions. These spatial and temporal distributions have not been measured on the scales required to demonstrate physical relationships among sediment properties, or on scales required to predict sediment acoustic, electrical, and mechanical behavior. New approaches need to be developed for remote and in situ sediment characterization. Modeling and experiments must include the effect of sediment spatial and temporal heterogeneity.

Sediment structure provides the common perspective required to unravel interrelationships among sediment-physical properties, quantify the effects environmental processes on sediment properties, and predict sediment behavior under stress. Any benthic boundary layer research program must therefore include the quantitative characterization of sediment structure at scales required to address these important scientific issues.

4.0 MAIN THRUST OF THE SRP

Sediment structure provides the key to understanding: (1) the physical relationships among sediment physical (bulk), acoustic, electrical, and mechanical properties; (2) the relationships between environmental processes and the spatial and temporal distribution of those sediment properties; and (3) sediment behavior under direct and remote stress (Fig. 2).

Sediment microstructure is defined here as micron scale, particle-to-particle and particle-to-fluid microfabric (e.g., relationship and orientation) and the related physiochemical state of the pore fluid and particle matrix. At these scales, biogeochemical processes and stress/strain related particle interactions dominate sediment structure.

Although two-dimensional, sediment structure has been determined by transmission (TEM) and scanning (SEM) electron microscopy, quantitative characterization is rare and three-dimensional quantitative characterization of sediment structure is unknown. The quantitative particle-to-particle and particle-to-fluid control of sediment behavior (acoustic, electrical, and mechanical response to stress or other stimuli), especially relating to fluid flow through a porous media and poroelastic moduli, remains to be defined.

Sediment macrostructure is defined here as millimeter to tens of centimeter scale pore-water, grain-aggregate structure. Macrostructure has been characterized in the laboratory and in situ by probes, X-radiography, acoustical and electrical tomography, optical sediment-water interface cameras, X-ray CT scans, optical microscopy, and various destructive geotechnical techniques (grain size, porosity, and strength related measurements). Bioturbation and other forms of biological and biochemical activity influence much of the sediment structure at these size scales. The heterogeneous structure of sediment probably dominates high-frequency acoustic volume scattering and may account for the anomalous acoustic penetration and propagation phenomena detected in recent field and laboratory experiments.

Sediment micromorphology includes sediment structures from as small as 10 cm (fine scale sediment layering) to meter size scales (1 m to 100 m). Spatial and temporal distribution and variability of sediment properties at these size scales are usually measured by acoustic, electrical, and optical remote sensing techniques. Physically driven environmental processes, such as erosion and depositional events, often dominate sediment-micromorphology structure and heterogeneity. This is the smallest size structure that can be routinely measured by the Navy's operational community and therefore must be used to "bridge the gap" among fine scale sediment structure, environmental processes, and the environmental inputs required by the Fleet.

Proposals will be solicited that address the scientific issues defined by common threads presented in section 3.0 and Figure 2. Modeling, hypothesis testing, and field experimentation will dominate the program. Financial constraints and research objectives dictate an interdisciplinary approach with a single set of focused experiments. A further focusing of the objectives of the SRP will be based on an evaluation and integration of proposed efforts. The emphasis of the proposals should be placed on the following topics:

1. New methods of three-dimensional characterization of sediment structure (microns to meter scale). Quantitative mathematical descriptions of three-dimensional sediment structure may include correlation lengths, fractal characterization, or require the development of new statistical techniques.

2. Effects of sediment macrostructure (e.g., heterogeneity, gradients, and layering) on high-frequency acoustic scattering, penetration, and propagation phenomena.

3. Effects of sediment microstructure on high-frequency seismoacoustic propagation (velocity and attenuation of the various types of compressional, shear, and interface waves)

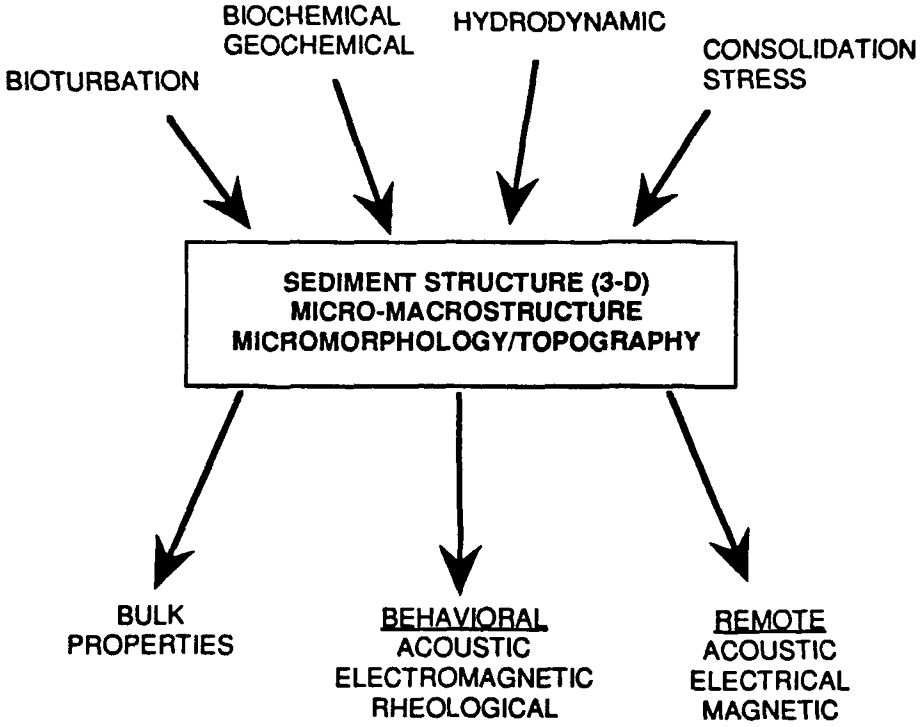

Figure 2. Relationships of sediment structure to environmental processes and sediment properties.

4. Physical relationships among sediment bulk, behavioral, and remotely sensed parameters.

5. Spatial and temporal variability of sediment properties.

6. Unifying theories connecting sediment structure and sediment properties.

7. The effect of environmental processes on sediment structure. A series of experiments will attempt to isolate and quantify the effects of biological mixing on near surface macrostructure, biogeochemical processes on sediment mechanical and poroelastic properties, biochemical oxidation of organic matter on pore-water chemistry, and processes responsible for gas bubble generation and distribution.

8. Relationships between fluid flow in porous media and sediment acoustic, electrical, and mechanical behavior.

Once the proposals are reviewed and selected, a meeting will be held with SRP principal investigators to coordinate activities and to develop a detailed experimental plan. The planning processes will start with model integration and simulation based on the conceptual framework depicted in Figure 2. Relationships between environmental processes and sediment structure, between sediment structure and sediment physical, behavioral, and remotely sensed properties, and among sediment parameters (e.g., shear wave velocity and shear strength) will be stressed. Investigators from such diverse fields as underwater acoustics, fluid flow mechanics, soil mechanics, geophysics, geoacoustics, and the *environmental sciences* need to start with a common understanding of each other and the overall program objectives. The model integration exercise will demonstrate gaps in knowledge and where new relationships or models need to be developed. It will also provide the framework for a sensitivity study to determine the potential importance of the effects of various environmental processes on both sediment structure and resultant properties and on the relationships among sediment properties. The results will provide the investigators with an additional method of hypothesis generation to guide the experimental (hypothesis testing) phase of the SRP. The results of the workshop will be used to generate detailed plans for the first field experiment to be held in May/June of 1993.

5.0 ACKNOWLEDGMENTS

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6.0 APPENDICES

APPENDIX A. Proceedings of the ONR Workshop on Sediment Classification for the Special Research Program on the Coastal Benthic Boundary Layer. T.G. Muir and C.S. Clay.

APPENDIX B. Seabed-Structure Interaction: Workshop Report and Recommendations for Future Research. R.H. Bennett, W.A. Dunlap, and H.J. Lee.

APPENDIX C. Interactions Between Environmental Processes at the Seabed and High Frequency Acoustics: Workshop Recommendations. D.R. Jackson and P.A. Jumars.

APPENDIX D. Proceedings of the ONR/SRP Coastal Optics Workshop. G.D. Gilbert

APPENDIX E. Summary of Magnetics in Coastal Regions. E.C. Mozley.

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Proceedings of the ONR Workshop on Sediment Classification for the Special Research Program on the Coastal Benthic Boundary Layer

Final Report under Contract N00039-91-C-0082,
TD No. 01A1036, Workshop on Sediment Classification

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PROCEEDINGS OF THE ONR WORKSHOP ON SEDIMENT CLASSIFICATION FOR THE SPECIAL RESEARCH PROGRAM ON THE COASTAL BENTHIC BOUNDARY LAYER

FINAL REPORT ON CONTRACT N00039-91-C-0082, Task 36

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ABSTRACT

A workshop of scientific experts in the area of sediment classification was held at Applied Research Laboratories, The University of Texas at Austin (ARL:UT), on 4 and 5 February, 1992, at the request of the Office of the Chief of Naval Research and the Naval Research laboratory, to examine the state of the art and future basic research that should be done in support of mine countermeasures and amphibious warfare. This report summarizes the findings, which include synopses on theoretical issues, experimental issues, measurement science issues, new instrumentation requirements, and future research options. A comprehensive bibliography was also assembled and is part of this report.

INTRODUCTION

In response to a request by the chief scientist of the subject Special Research Program (SRP), Dr. Michael Richardson, a workshop was held in February, 1992 at Applied Research Laboratories, The University of Texas at Austin (ARL:UT), to examine sediment classification, review the state of the art, identify scientific issues facing the Navy, and prioritize and chart the direction of future research on sediment classification in support of mine countermeasures (MCM) and amphibious warfare (AMW). The agenda for the workshop is in appendix A of this report.

WELCOMING AND OPENING PRESENTATION

Dr. Mike Pestorius, director of ARL:UT, welcomed the participants to the laboratory. Then, Dr. Richardson gave an opening presentation, an overview of plans for the SRP, emphasizing that it should address environmental processes affecting MCM and AMW operations in shallow water.

ATTENDEES

- Mr. John Cornette, ONR
- Dr. Joseph Kravitz, ONR
- Dr. Thomas Kinder, ONR
- Dr. Michael Richardson, NRL
- Mr. Douglas Lambert, NRL
- Dr. Edward Mozley, NRL
- Dr. Darrel Jackson, APL/UW
- Dr. Douglas Todoroff, NCSC
- Dr. Timothy Stanton, WHOI
- Dr. Lawrence Mayer, Univ. of New Brunswick
- Dr. James Sabatier, NCPA
- Dr. Nicholas Chotiros, ARL:UT
- Dr. Peter Thorne, ARL:UT/Proudman Oceanographic Laboratory
- Dr. Joseph Gettrust, NRL
- Dr. William Kuperman, NRL
- Dr. Robert Stoll, Lamont-Doherty
- Dr. Lester LeBlanc, Florida Atlantic Univ.
- Prof. Em. Clarence Clay, Univ. of Wisconsin
- Dr. Thomas G. Muir, ARL:UT
- Dr. Christian de Moustier, SIO:MPL:UCSD
- Dr. Nicholas G. Pace, Bath University
- Dr. Tokuo Yamamoto, Marine & Atm. Science Univ. Miami
- Dr. Brian Bourgeois, NRL
- Glen McLeroy, Technical Marine Services
- Dr. John Hildebrand, Univ. of Calif.

STATE OF THE ART REVIEW

Each of the participating scientists was asked to give a 15 minute brief on their work in sediment classification, in recognition of the fact that each of them and each of their laboratories represents a national resource in this area. One of the participants (Mayer) represents a Canadian laboratory, and two of them (Thorne and Pace) represent U.K. laboratories. The purpose of the briefs was to introduce the participants to identify expertise, and start the interaction process.

Dr. Mayer led off the briefs with an impressive survey of Canadian programs involving multi-instrument, three dimensional mapping of sea floor parameters. Mr. McLeroy, the first to use chirp sonar for sediment classification, discussed empirical relationships between echo behavior and sediment properties pertinent to mine burial. Dr. LeBlanc summarized his extensive experience with a wideband chirp sonar for sediment classification and the extraction of geoacoustic parameters. Dr. Stanton discussed the statistical behavior of echo amplitudes as related tosea floor roughness.
Dr. de Moustier discussed obliquely incident beams on the sea floor, echo data processing and the extraction of roughness and volume scattering functions.
Dr. Todoroff discussed mine burial and the use of nonlinear, parametric sonar for sediment classification.

Mr. Lambert presented results from a 15 kHz normal incidence acoustic sediment classification system, which he used to obtain sediment data required for mine burial prediction. Dr. Chotiros discussed buried object detection experiments and the role of gas in the sediments on the acoustic processes. Dr. Thorne discussed sediment transport due to hydrodynamic turbulence at the sea floor and a calibrated system to measure it. Dr. Pace discussed side scan sonar operated in an interferometer mode for low grazing angle backscattering measurements to determine the effect of porosity variations.

Dr. Stoll discussed the Physics of particulate sediments in the context of the Biot-Stoll theory, as well as in situ P and S wave measurements and data inversion techniques used to yield geoacoustic models of sediment parameters versus depth. Dr. Gettrust discussed a deep tow P wave system involving a source and a multi element towed array that was used to infer shear wave properties in stratified sediments from critical angle analyses of frequency versus grazing angle contours. Dr. Yamamoto discussed several seismo acoustic measurement techniques used to yield sediment parameters, including the inversion of gravity wave driven seismometer data, bore hole – bore hole tomography, and multi element, laterally towed arrays. Dr. Sabatier discussed seismo acoustic measurements in air saturated soils, particularly acoustic - seismic transfer functions that result from the presence of impermeable, sub-soil inclusions. Dr. Hildebrand discussed several seismo acoustic techniques used in deep water measurements, as well as a time domain electromagnetic (EM) technique involving magnetic coil source and receiver to measure EM velocities in the water and sediment. Dr. Jackson discussed the problem of sea floor scattering, particularly distinguishing rough surface scattering from sediment volume scattering.

Finally, Dr. Ed Mozley presented data collected with an active airborne electromagnetic system, which appears useful in charting water depths and sediment conductivity. These parameters provide the environmental inputs required to optimize electromagnetic minesweeping.

DISCUSSION FOLLOWING THE PRESENTATIONS

The central scientific issue facing this portion of the SRP is the meaning of sediment classification and how sediment classification is related to measurements and mechanical properties important to MCM and AMW. Sediment classification has long been used as a fundamental approach in geological investigations, and geologists have devoted considerable effort to this subject. Geologic sediment classifications are usually based on sediment texture (grain size) and grain mineralogy, but may include numerous other components, biologic content, and structures. In addition, geologists employ the concept of facies to define and differentiate sedimentary units as to origin, placement, and age on the basis of distinguishing attributes. While the geological classifications are useful, MCM applications require a system for classification of the shallow sea floor that is closely based on the mechanical properties of its composite

materials and our ability to remotely sense these properties. The mechanical properties and remotely sensed properties are a matrix of information that can be subjected to factor analysis. One can expect that the properties will form a few clusters and that the clusters will form the basis for sediment classification.

Seismo acoustic remote sensing measurements give geoacoustic parameters such as compressional and shear wave velocities, compressional and shear wave attenuations, and densities. Seismo acoustic profiles give the structure along the survey track. These geoacoustic parameters are related to the "primitive" parameters in the Biot equations for a fluid filled porous medium. The primitive parameters are the sizes, shapes, and densities of grains; the permeability; the frame modulus; fluid modulus, etc. The primitive parameters may be more closely related to the mechanical properties than are the geoacoustic parameters. Examples of macroscopic mechanical properties are shear strength of drained and undrained sediments, elastic moduli, porosity, permeability, density, and structure. Smaller scale mechanical properties are density of grains, grain sizes, cementing, packing, and sorting. At the sediment-water interface grain microtopography, bottom roughness, bed armoring and particle transport are important.

Three key elements of the classification task were examined in the workshop. They are: **theoretical relations** between acoustic, seismic, and electromagnetic parameters and the mechanical properties of sediments, **experimental issues** needed to resolve theoretical questions and develop the theory, and **measurement science**, needed to develop the art of sensing and classifying the sediments. Each of these elements will be discussed separately. The culmination is combining the information from these three elements and applying methodology such as cluster analysis to construct a sediment classification method.

THEORETICAL ISSUES

Falling objects such as mines can penetrate the seafloor if it is soft, sit on the seafloor if it is hard, be buried by moving sediments such as sand ridges, and/or have the sediments scour around and under them, in high currents, eventually sinking and burying them. What actually happens depends on the mechanical properties of the sediments and the local currents. The detection and classification of the mines in this environment, by acoustic, seismic, or electromagnetic means is equally complex.

Since the measurable geoacoustic parameters such as the compressional and shear wave velocities, attenuations, and densities are only indicative of the mechanical parameters, theoretical research is necessary to relate the geoacoustic parameters to the geotechnical parameters that govern the processes mentioned above. The undrained shear strength appears to be a very important geotechnical parameter, because it is the principal mechanical property that determines the short term penetration resistance (bearing capacity) of the sediment and hence will control the

depth of mine burial in soft sediment. It is also important in problems involving offshore foundations, anchor resistance, cable burial, and slope stability.

An example of the issues mentioned in the previous paragraph is the remote measurement of the undrained shear strength of ocean sediments by measuring the instantaneous velocity of an expendable probe as it falls through the water column and penetrates the sea floor. Such a device is marketed by the Sonatech Corp. [see paper by Cyr in the bibliography]. The velocity is determined from Doppler measurements of a sound source on the probe, as it decelerates. At issue is the relationship of the deceleration of the probe to the undrained shear strength, and other geotechnical parameters, especially in shallow, sandy sediments. This is a fundamental theoretical and experimental problem, where improvements and expansions to new applications can be made.

The theory of dynamic penetration into seafloor sediments as used in reducing Doppler Penetrometer data is largely based on the work of D. True. It has been modified by the Naval Civil Engineering Laboratory (NCEL) for application to the Doppler Penetrometer. The theory has had very little research when compared to acoustic models for sediment evaluation. However, the theory has been used with significant success. Working Doppler Penetrometers are providing useful data.

The theory is most applicable to cohesive soils in which the variation of strength with strain rate is significant, but reasonably well understood. The theory has been applied to penetration into the sands. However, while the limits of the very significant change of strength of strain with strain rate can be calculated, the variation as a function of strain rate is not known as well as that of cohesive soils. Presently the same function of strength versus strain rate is used for both cohesive and sand sediments. Also, there is an inability to relate the undrained, or partially drained strength of sand measured with the Doppler Penetrometer to static strength.

The Biot theory was derived for the fluid filled porous solid. Conventionally, the fluid is water and is nearly incompressible A number of experiments, both field and laboratory, have confirmed the usefulness of the theory. Since the Biot theory, although complex, describes the simplest version of porous sediments, it has been developed as a framework that includes other theories as limiting cases, i.e., fluid, elastic, theromviscous, etc. Two theoretical extensions concern pore spaces that are the light fluid (gas) limit and two component fluids that are mixtures of water and gas.

Objectives of the theoretical research are to determine the relationships of the **geoacoustic** parameters and **geotechnical** parameters such as the undrained shear strength and the elastic moduli on the **primitive** parameters in the Biot theory: i.e., the porosity, the overburden pressure, the permeability, the fluid modulus, the frame modulus, etc. The effects of bonding, lithification, electrochemical bonds, and overburden pressure are complications that can be included in the course of the research.

Wave propagation in porous media and the elastic behavior of the media are frequency dependent. For these applications, the frequency ranges of interest for MCM applications are: shear waves, 100 Hz to 2 kHz and compressional waves, 5 to 500 kHz. This enables us to focus on the sediment depths of interest, i.e., 0 to 2 m in hard sediments and 0 to 10 m in soft sediments.

The Biot theory and its extensions are the bridge to go from measurements of the acoustic-seismic parameters to the geotechnical parameters and classifications. The theoretical research is quite general and other applications involving extensions of the theory include the intrinsic as well as geometric attenuations of seismo acoustic waves, volume scattering by grains, consolidation and compaction of near surface sediments, and liquification of sediments.

A new problem has recently appeared, which may be significant to buried MCM. It involves the phenomenon of "wave-induced breakout", which may cause partially buried mines to be lifted off the seafloor during severe storms. This sort of breakout has occurred to partially buried pipelines on a number of occasions and some research is currently underway; however the phenomenon is not fully understood and may be an important topic with regard to the mine location problem. A reference (Foda et al.) is included in the bibliography.

Finally a comment is offered on the theory that would be required to understand acoustic detection of buried mines. A buried mine is below the surface of the air/ground interface or the water/sediment interface. In both cases, these media are layered and porous. This problem of an inclusion in a porous layered medium near the interface is of fundamental importance in understanding the physics of detection. The detector, in either case, will be a stand-off type with source and receiver in the top medium (air or water). This further complicates the problem, because the impedance of the surface is frequency dependent. The complete problem to be addressed is a point source above a complex impedance pro-elastic boundary with a buried inclusion. These issues have not been addressed in the literature.

Some important issues for theoretical development in sediment classification include:

1. What are the mechanisms of sound penetration into ocean sediment and their relative importance, particularly at shallow grazing angles?

2. What types of scattering mechanisms are present in the sediment volume, and which scattering theories are most appropriate for each mechanism (single-scatter, multiple scatter, or diffusion)?

3. What is the theoretical model for the empirical relationships observed between shear modulus and shear strength, proposity and depth, penetration depth and shear strength etc.?

4. What is the theoretical model for the frequency dependence of bottom backscattering strength as a function of frequency, and can it be used as a bottom classification tool?

5. What is the theoretical basis for the observed backscattering strength as a function of grazing angle, for shallow grazing angles, and can it be used as a bottom classification tool?

6. What is the influence of gas bubbles on acoustic backscattering strength and hence on acoustic bottom classification algorithms? Are we really classifying the sediment or the bubbles?

7. What is the theoretical model for gas bubble migration between water and sediment?

8. Can we develop simple theories of low grazing angle backscatter to feed into the use of side scan sonar for quantitative sediment classification?

9. Can we develop a scattering component to Biot theory. Could it be done by using Biot theory for propagation and splice in a scattering model and balance energies?

EXPERIMENTAL ISSUES IN SEDIMENT CLASSIFICATION

For a number of reasons, acousticians and geophysicists have studied the near surface sediments much less than they have studied deeper materials. Consequently there is much that we need to know about these materials for navy applications. The needed research is small scale because, for example, the layers may be a few centimeters thick and vary over a fraction of a meter, laterally. Detailed surficial geoacoustic surveys may consist of profiles of perhaps 10 to 100 m length. Normal incidence profiler resolution of layers of 10 cm thickness requires signal frequency band widths of more than 15 kHz. These shallow sediments can also be studied by electromagnetic methods. The resistivity of a porous material depends of the porosity, permeability, tortuosity, and the resistivity of the fluid. The uses of resistivity and electromagnetic measurements for "well logging" in the oil industry and surveying in the mining industry are well known.

The structures of near surface sediments can change over periods of hours to years and the times are strongly dependent on the local environment. Sediments at the water sediment interface are subject to waves and currents. Water motions due to waves and bottom currents move the sediment particles about. The out flows of rivers are sources of sediment deposits and can change after floods and storms. Sediments also have their own behavior. If disturbed some sediments may become very soft and liquefy due to excess pore-water pressure caused by the disturbance. Later as the excess pressure dissipates, the sediments may regain their initial strength. In other

kinds of sediment, disturbance may cause long term loss of strength due to the disruption of interparticle bonds. In these sediments the initial strength may never be regained or may only be partially restored by slow thixotropy.

Benthic animals live in and on the sediments. Some animals burrow into the material and others push it around. Some burrowing species destroy the mechanical rigidity of the sediment while others strengthen it by excreting skeletal structure. Fishermen often use bottom trawls and their trawls can both reshape the bottom and harvest scientific instruments.

The geoacoustic properties are complicated functions of x, y, z, and t. The properties can be displayed as charts and cross-sections. For data reduction, the properties can displayed as a the sum of a mean structure and a variable component. By regarding the variable component as being stochastic, the variable component can described by spatial spectra and correlations.

It is essential to have "ground truth" data for experimental analysis and verification of theory. Surface topography can be measured by using stereo photographs, mechanical surveys, and high resolution echo sounding surveys. It is more difficult to establish ground truth in depth structure because the sample, a vertical core from a drill hole, only shows what is in the core. Core data can be supplemented by using geophysical profiles to connect one drill hole to another. Hole to hole geoacoustic tomography gives a cross-section of the geoacoustic parameters that can be compared with seismic-acoustic profiles from the surface and cores from the drill holes.

Shear strengths and shear wave velocities are crucial parameters for the naval applications at hand. Shear strengths are measured in situ. Shear wave velocities can be measured remotely, however special techniques are needed. The conversion of compressional waves to shear waves and visa versa depends on the incident angle, topography and other parameters. At vertical incidence, the conversion is zero because vertically incident compressional waves on a plane interface simply do not excite shear waves. As the angle of incidence increases, the conversion of compressional to shear waves increases. The existence of shear propagation in a layer causes the reflection at grazing angles less than critical, to be less than perfect, because some energy goes into the lower medium as shear waves. The shear waves can scatter from inhomogeneities and rough interfaces, and some of the shear wave energy converts to compressional waves, while the scattered waves appear as back scattered energy. The practical importance of the converted waves depends on shear wave velocity and attenuation in the sediments.

The issues and challenges facing experiments in sediment classification are illustrated in the questions that follow.

1. Sediment Variability. Most measurements result in description of variability in 2-D where, in fact, the sediment varies in 3-D. To measure in 3-D is a great experimental challenge, but is essential.

2. Discrimination Between Roughness and Volume Scattering. Both roughness and volume inhomogeneities are potential sources of acoustical scattering. Proper classification of sediment requires discrimination between the two phenomena.

3. Deterministic versus Statistical Bathymetry versus Texture. The bathmetry may not be known in all locations and/or all scales hence both deterministic and statistical information are required in describing the sediment.

4. Integration Of Various Independent Techniques. No one technique can fully describe the sediment, hence acoustics, E.M., seismic, ground texture, information must be collected and compared in a meaningful way.

MEASUREMENT SCIENCE ISSUES

The purpose of environmental measurements for MCM is to survey and chart the geoacoustic-seismic and electromagnetic parameters that can, by analysis, yield the needed properties of sediments, to predict such factors as mine burial and detection. Since there are many kinds of parameters, many different kinds of measurements and equipment are needed.

Typical surveying techniques are normal incidence reflection and sub-bottom profiling, multibeam sonars for measuring bottom topography, side scan sonar with and with out interferometric processing, and seismic inversion with P wave sources and multi element streamers. All of these systems can be configured to operate in many frequency ranges and water depths.

A second class of surveys uses instruments that are placed on the bottom and buried in the sediments. For example, direct observation of shear waves requires geophones on or in the sediment (Geophones are commonly used as particle velocity sensors). A string of geophones along the sediment interface can measure the dispersion, velocities, and depth dependence of shear interface waves and other wave types. Geoacoustic tomography uses vertical arrays of sensors in a drill hole and sources in another drill hole. The tomographic inversion gives a cross section of parameters such as wave velocities and attenuation versus range and depth between the holes. With digital recording of data, the results of experiments can be processed to compute many parameters.

A third class of surveys involves expendable instruments, dropped into the bottom. One such instrument is the Doppler Penetrometer, which attempts to measure the undrained shear strength. The deceleration of the penetrometer as it enters the seafloor results primarily from the shear resistance of the sediment.

The issues and challenges facing measurement science for sediment classification are illustrated in the questions that follow.

1. What are the contributions of the rough surface and sub-bottom inhomogeneities to the normal incidence reflected signal? Are reflected signals affected by shear wave velocity? (Ping broadening has been reported.)

2. What additional information do multibeam and side scanning sonars give about the surface roughness, the subsurface inhomogeneities, and shear velocities?

3. What are the sediment attenuations for P waves in the 200-20000 Hz band of frequencies.? There is a gap in the experiment data between 100 Hz and 20 Hz.

4. What is the relation between shear velocity and shear strength? Can we remotely measure shear strength? These measurements are best done in the field to eliminate problems with simulating sediments in the laboratory.

5. What are the contribution of bubbles to the P and S wave velocities? What are mechanisms for bubble creation? At low frequencies, bubbles have been found to lower the compressional wave velocity of sediments to a fraction of their usual velocity. Wave velocities are dependent on frequency and bubble concentrations. Considerable work has been done on these questions, and the results need to be applied to the application at hand.

6. What are the viable physical parameter relations in real world sediments? Can a set of sediment type locations and a full set of geoacoustic measurements at each site provide an adequate database to scientifically establish the relationships?

7. Can factor analysis determine the sub set of physical parameters that are needed to classify the sites?

8. At present, Doppler Penetrometers function well in mud bottoms. Can they be designed and calibrated to work in harder sediments such as sands?

RESEARCH PROGRAM OPTIONS

Expansion of ongoing research

It should be recognized that in sediment classification, particularly the three areas addressed by this workshop (theory, experiments, and measurement science), there has already been a start made by ONR sponsored investigators. It is reasonable to expect that those individuals may likely continue theoretical and experimental research under the new SRP, focusing on new problems identified in the workshop. For these projects, the level of individual effort may continue much as it is now. Candidate projects are offered below in an annotated list.

1. One of the unknown parameters of seabed scattering is the volume contribution. There are no field measurements in the open literature combining data on surface statistics and surficial sub-surface volume inhomogeneities were reverberation measurements have been compared critically with theory. This area is ripe for investigation both at sea and in the laboratory. Biot's theory could be employed for sound propagation in sediments with an extension to incorporate heterogeneity and a volume scattering component could be included to give a first order solution to the scattering problem. This work has merit theoretically and for MCM.

2. Parametrization of surficial roughness and sub-bottom volume scattering by seismic methods. This theoretical/experimental study would provide roughness parameters such as rms roughness and roughness spectrum and volume scattering parameters such as mean scattering cross-section and correlation distance. The parametrization would help classify the sediments as well as provide inputs in scattering models to predict acoustic reverberation.

3. Development of Doppler Penetrometer techniques requires a study of the variations in strength of sand with strain rate. The instrumentation to do this may already exist at the Waterways Experiment Station. This does not need to be done under penetrating object conditions. Rather, the tests would be performed under impulse conditions in laboratory test equipment used for measuring soil strength. Test sample boundary conditions would need to model that of sediment near a penetrating object. Some laboratory studies of penetrating objects could be necessary; particularly in sand. The advantage of laboratory studies will be controlled sediment conditions and instrumentation, and the ability to vary the penetration velocities over a wide range.

4. Establish a parametric relationship between shear wave velocity and shear strength based on the common dependence of the two responses (one large strain and the other very small strain) on certain of the primitive parameters such as porosity, overburden pressure, over consolidation ratio, etc.

New direction research at new sites

The new efforts under the SRP may need to be structured to effectively address the goals of the SRP, including the research planned by the other workshops. Sediment classification is a key element in the work planned by the workshop on seabed structure and acoustic interaction, as well as the workshop on environmental processes and high frequency acoustics. All of the workshops recommend the development of theory and the conduct of both laboratory and field measurements. It is important to conduct sediment classification work, both with existing techniques and those under research and development, at the same testbed sites that will be used by the other groups. It is also likely that the sediment classification segment of the SRP will require its own testbed sites where issues more specific to sediment classification can be addressed with in-depth ground truth data and other special assets. By way of example, the following annotated list of candidate sites that could be addressed is offered.

1. The "field sand" testbed proposed by the seabed structure and acoustic interaction workshop, tentatively planned to be a "clean" sand sediment at the end of a pier or some other logistically convenient site.

2. The "harbor mud" testbed proposed by the seabed structure and acoustic interaction workshop, tentatively planned for a natural mud sediment with an "organically rich" environment.

3. The "site of substantial horizontal and vertical heterogeneity" proposed by the seabed structure and acoustic interaction workshop, tentatively planned for environments having "estuary inlet complexes, with lenses of varying bed material produced by channel migration, to more gradual gradients seen in estuary sounds."

   At these sites, it is recommended that the following topics be examined.

   a. Design and perform new laboratory and field experiments that will allow the measurement of p- and s-wave attenuations in the frequency range of 100 Hz to 20 kHz.

   b. To further validate models of low grazing angle backscatter data on the lateral variability of the surficial layers on a centimetric scale is required. This is a challenging problem of ground truthing. The general problem of ground truthing in sidescan sonar work, is one point samples against

areal data and may never be solved realistically. However, there is so little knowledge concerning lateral variability on the fine scale demanded that this is worth addressing.

c. Integration of swath bathymetry and sidescan sonar to obtain maps of actual backscatter strength and its angular dependence is also of interest. This would follow from the necessary full instrumentation and navigation facility in swath bathymetric systems. The marrying of topographic and sidescan data would add new dimensions to knowledge of the seafloor.

4. One of the most important objectives of the SRP is to find the relations among the **geotechnical** parameters such as the shear strength, the **geoacoustic** parameters and the **primitive** (physical) parameters of the shallow water seabeds. A systematic set of experiments to do this would be the Standard Penetration Test (SPT), the cross-borehole P and S tomography experiments, the shear modulus profiler experiments and the chirp sonar echo measurements. All of these experiments may be best performed from a jack-up platform.

   The SPT test will provide the shear strength data and sediment cores for the **primitive** properties. The SPT boreholes, say 20 m deep, will be used for the cross-hole tomography tests.

   The shear strength data from SPT will be related for the first time to the P- and S-wave velocity and attenuation structures measured from the cross-hole tomography tests and the pulse broadening of the Navy chirp sonar. The tomographic data will be used to model the pulse broadening. These set of experiments from the jack-up platform will be easily repeated at the various shallow water sediment sites.

5. The sediment properties in shallow water are time dependent. The evolution of the loss of shear strength due to liquefication by storm waves and subsequent strength recovery in sands, silts, and clays may be quite different. We would need a long term (say 12 months) observation of the forcing mechanism and the shear strength with depth profile. For example, a Bottom Shear Modulus Profiler (BSMO) will make contemporaneous recording of wave directional spectra (forcing) and temporal change of shear modulus profile before, during, and after a storm. This system penetrates gassy sediments also. This type of long term observation of sediment properties/environmental forces at several sedimental provinces may greatly advance our knowledge in sediment classification in shallow water and greatly improve the Navy's MCM capability.

Instruments

It is anticipated that those involved in experiments and measurement science for sediment classification work will design and develop their own instrumentation, so as to perform experiments and measurements that are new and cannot be done with existing instruments. This does not mean that procurements of general laboratory instruments will be unnecessary. It should be recognized that the development of new sediment classification instruments may require a significant commitment of funds. By way of example, the following annotated list of instruments that may be needed or developed is offered:

1. Seismic source with **2-D** steerable receive array to be towed(?). This system would provide backscatter versus angle (via narrow pencil beams) as a function of frequency. Surficial roughness and volume scattering information would be obtainable from this system. Sources, hydrophones, and acquisition electronics all commercially available. Software development, array design, testing are main challenges/time sinks.

2. A field measuring apparatus that will measure shear strength and shear wave velocity in one integrated operation. The apparatus should be simple and robust and should allow rapid deployment from an unanchored ship.

3. An *in situ* instrument to measure gas bubble population distribution in ocean sediments.

4. An *in situ* instrument to determine the chemical composition of sediment gas bubbles.

5. An instrument to measure sediment inhomogeneity for estimating sediment volume scattering.

6. Standard Penetration Test (SPT) boring and cross-hole tomography equipment. A standard SPT equipment will be operated from a jack-up platform to measure the blow counts (N-value) and to collect sediment core. The SPT boreholes will be used for cross-hole tomography experiments. The sources, receiver arrays, and data acquisition system for the p-wave tomography exist. The S-wave sources have to be developed and tested. Down-hole airguns and sparkers may be good S-wave sources, which are readily available.

7. Seven BSMP's are available. Self-contained digital recorders have to be built or borrowed from the ONR-OBS Program, Code 1125GG.

SUMMARY

The state of the art of the science of sediment classification was examined by an ONR workshop of experts, from the standpoint of future needs for MCM and AMW. Issues were identified and analyzed in the areas of sediment classification theory, experiments, and measurement science. A comprehensive bibliography was assembled. Research program options were identified for both the expansion of ongoing research at existing laboratories and test sites as well as new direction, research at different laboratories and test sites. The need for the development of new research tool instruments was also examined.

APPENDIX A.

AGENDA

Tuesday, 4 February, 1992

0830 Call to Order and Welcoming, Tom Muir and Mike Pestorius, ARL:UT
0840 Chief Scientist's Overview, Mike Richardson, NRL/ONR

Summary Briefs on Expertise, On-going Work; Tom Muir, moderator

0900 Larry Mayer, Univ. New Brunswick
0915 Glen McLeroy, Technical Marine Services
0930 Lester LeBlanc, Florida Atlantic Univ.
0945 Tim Stanton, Woods Hole Oceanographic Inst.
1000 Christian de Moustier, Marine Physics Lab., Scripps, UCSD
1015 Doug Todoroff, Naval Coastal Systems Center

1030 Break, coffee and donuts

1045 Doug Lambert, Naval Research Lab.
1115 Nick Chotiros, Applied Research Lab.
1130 Peter Thorne, Proudman Oceanographic Lab., U.K. (visiting @ ARL:UT)
1145 Nick Pace, Dept. Physics, Bath Univ., U.K.

1200 Working lunch provided by ARL:UT

1230 Bob Stoll, Lamont-Doherty Geol. Observatory, Columbia Univ.
1245 Joe Gettrust, Naval Research Lab.
1300 Tokyo Yamamoto, Marine & Atmos. Science Dept., Univ. Miami
1315 James Sabatier, National Center for Physical Acoustics
1330 John Hildebrand, Marine Physics Lab., Scripps, ACID
1345 Darrell Jackson, Applied Physics Lab., Univ. Washington

1400 Identification of Scientific Issues, Clarence Clay, Univ. Wisconsin
(Group discussion to identify areas of importance and delineate issues facing future research in each area.)

1500 Break, coffee and cookies

1515 Continuation of group discussion
1700 Adjourn

1830 No-host bar and dinner, County Line On The Lake Restaurant, see map, specializing in Texas Barbecue

Wednesday, 5 February

0830 Prioritization of Scientific Issues

1030 Break, coffee and donuts

1045 Options for SRP Research Programs

1200 Working Lunch provided by ARL:UT

1230 Review, Summary, and Recommendations
1400 Adjourn

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Intrinsic to the topic of Seabed-Structure Interaction (S-SI) of objects coupled with the sea floor is the dynamics of the "system." The dynamics involve environmental forcing of the object and the seabed, the fundamental properties of the geological material, the size an shape of the object, and the time-dependent processes associated with the coupling of the water column, seabed, and the object. Thus, the most crucial S-SI research problems to address in the Coastal Benthic Boundary Layer Special Research Project (SRP) should focus on the dynamics and time-dependent processes affecting objects coupled to the sea floor. The research efforts should include a range of scales from micro to macro but largely focused on the dynamics and processes in proximity to the object rather than broad scale geological oceanographic processes. Much is to be gained by interdisciplinary research well focused on specific S-SI phenomena.

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SEABED-STRUCTURE INTERACTION

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SUMMARY OF RECOMMENDED RESEARCH THRUSTS

SEABED-STRUCTURE INTERACTION
COASTAL BENTHIC BOUNDARY LAYER SPECIAL RESEARCH PROJECT

Intrinsic to the topic of Seabed-Structure Interaction (S-SI) of objects coupled with the sea floor is the dynamics of the "system." The dynamic process include environmental forcing of the object and the seabed, the fundamental properties of the geological material, the size and shape of the object, and the time-dependent processes associated with the coupling of the water column, seabed, and the object. Thus, the most crucial S-SI research problems to address in the Coastal Benthic Boundary Layer Special Research Project (SRP) should focus on the dynamic and time-dependent processes affecting objects coupled to the sea floor. The research efforts should include a range of scales from micro to macro but largely focused on the dynamic processes in proximity to the object rather than broad scale geological and oceanographic processes. Much is to be gained by interdisciplinary research well focused on specific S-SI phenomena.

The S-SI Workshop addressed two important technical topics: (1) Sediment Transport: Scour and Fill, and (2) Geotechnical: Seabed Mechanics. Numerous research topics were identified in each of the two technical areas and additionally two general subtopics were identified as (A) Object Sensing Methods (Detect/Classification) and (B) Sediment Properties Measurements and Data Analysis. Although important to the understanding of S-SI processes, these two subtopics will be thoroughly developed by other SRP workshops and the details will not be discussed here. The most important topics recommended to be part of the SRP, S-SI basic research program, are outlined below.

The purpose of the R&D in Sediment Transport, Scour and Fill, is to improve existing models and create new reliable models of Wave-Current-Seabed-Structure Interaction (W-C-S-SI). This is to be accomplished through quantitative studies of the combined effects of W-C-S-SI directed at understanding the dynamics of the coastal environments and time-dependent processes. Studies should include all sediment types common to coastal environments; sands, silts, clays and organic rich deposits, and mixtures of each.

<u>Sediment Transport: Scour and Fill</u>

- o Development and testing of physical models incorporating the time-dependent S-SI interactions. Small-scale and full-scale studies are needed.

- o Understanding of scaling effects and scaling laws involving S-SI processes; facilitated by laboratory and field studies.
- o Understanding of the turbulent hydrodynamic variations (small to large scales) induced by the presence of an object in the flow field.
- o Understanding of the nonlinear wave-current interactions with the sea floor and the object coupled with the sea floor.
- o Understanding of the time scales and transient phenomena driving and controlling pore water flow in proximity to bottom-sitting objects in dynamic motion.
- o Understanding the role of dynamic pore pressure on sediment transport and stability around a solid body coupled with the sea floor (muds and sands) and driven by different (frequency) environmental wave-current forces.

The purpose of the R&D in Geotechnical, Seabed Mechanics, is to create a reliable predictive model of the object-seabed mechanical interaction. The sediment reactions are a combination of:

(a) stresses and deformations caused by direct interactions between seabed and object.
(b) stresses and deformations caused by the regional hydrodynamic field.

The effects of the combined system (a)(b) are exhibited by a range of phenomena

1. static—no deformations—object at rest
2. slow settlement and displacements of supporting sediment
3. rocking, gap development, self-embedment
4. sliding, gouging, etc.

To accomplish development of a reliable model, studies are required in diverse areas of sediment structure interactions.

<u>Geotechnical: Seabed Mechanics</u>

- o Understanding of the processes responsible for gap formation in cohesive sediments by object/sediment/fluid interaction.
- o Understanding of the role of gas charged sediment in the dynamic behavior of object-sediment coupling.
- o Understanding of the wave-induced sediment deformations stresses and pressures (total stress and pore pressures) of objects in dynamic motion on a clayey (mud) sea floor when object is allowed to rock, sway, heave, etc.
- o Understanding of the development of excess pore pressure and degradation of sediment strength under dynamic loading conditions with object coupled with the seabed; the importance and influence of permeability, sediment type (grain size and mineralogy),and microfabric on the time-dependent processes.

- o Understanding of wave induced pore pressure attenuation with subbottom depth in sands, silt, clays and admixtures and an understanding of the energy transfer in different sediment types under various wave climates in coastal areas.
- o Understanding and development of modeling laws for scaling from laboratory tests to field conditions.

The above topics will largely dictate what types of instrumentation are required in developing laboratory and field studies and what specific environmental data and seabed properties measurements are needed.

SEABED-STRUCTURE INTERACTION

INTRODUCTION

Background...The topic of Seabed-Structure Interaction (S-SI) is one of four crucial research elements in the Coastal Benthic Boundary Layer Special Research Program (SRP). The program is designed to address important basic research issues directed toward support of the U.S. Navy's coastal, mine counter measures (MCM), and amphibious mine warfare (AMW) operations. The other three topics of interest to the SRP include (1) Environmental Processes and High Frequency Acoustic Scattering/Propagation Phenomena at the Benthic Boundary Layer, (2) Sediment Classification Methodologies Required for Improved MCM Systems Performance and Performance Prediction, and (3) Processes Responsible for Fine-Scale Electro-Magnetic and Electro-Optical Variability in Near Shore Marine Sediments. These three topics are not directly addressed in this report although the basic research involved in each of the four topics has important synergism that supports the Coastal Benthic Boundary Layer SRP. The research thrust that links the four major research topics is the objective to improve the performance and performance prediction of MCM systems used to detect, classify, and neutralize mines located within or on the sea floor. This is accomplished through basic research directed toward understanding environmental processes that affect MCM and AMW operations in coastal waters.

The technology issues involving S-SI processes include the predictions of mine burial at impact and by scour, sand wave migration, and deposition including well defined but poorly understood S-SI mechanisms. A host of technical problems exist for basically all marine sediment types including sands, silts, clays, and admixtures of each. The environmental processes and the types of data requirements necessary for addressing technical problems in S-SI have been summarized by Valent et al. (1988) (Tables 1 and 2). The complex marine environment combined with the high spacial and temporal variability of sediment properties and processes, at the sediment-water interface and within the seabed, provides a unique challenge for future research on the subject of S-SI.

The coupling of an object with the seabed and their combined dynamic response is described as S-SI. Implicit in the definition of S-SI is the importance of the forcing by and the interaction with hydrodynamical processes in the benthic boundary layer. Because the marine environment is characterized by a variety of geological materials, seabed properties, and hydrodynamic processes, the problems of modeling, analysis, and prediction of S-SI time-dependent processes are complex; and thus present capabilities that are

Table 1.1-1. Potential S-SI problems for consideration.

Environmental Processes (mass processes)

- Bottom failure (without structure on bottom)
  - — Environmental forcing functions, e.g., waves, earthquakes (seismic shock), internal waves
  - — Scour-oversteeping by sedimentation (may be seasonal), bioerosion, iceberg keels
  - — Strength decrease: pore pressure increase due to:

    waves
    osmotic pressure changes
    biogenic methane production
  - — External, man-induced: ships, construction activities, weapons effects (shock waves etc.)
  - — Tide-induced flow slides (sands / silts)
  - — Collapse of bottom due to environmental conditions (little or no translation)
- Nepheloid layer (high-density bottom water)
- Sand wave migration due to storms
- Changes in water column characteristics due to differences in bottom characteristics (properties), i.e., wave degradation characteristics, water velocity, pressure

Processes Due to Structure on Bottom (localized processes)

[structure configuration (effects of) and changes produced by currents and waves]

- Scour: sand/silt/clay scour resulting in the following:
  - — settling
  - — tilting
  - — movement
  - — burial, differential settling
- Localized strength degradation and pore pressure changes due to repeated loading (cyclic loading of structure on bottom)
  - — thermal gradients (frozen ground/permafrost) freeze-thaw
- Bottom failure/bearing capacity
  - — initial failure and failure due to strength degradation
  - — prediction of penetration depth
  - — breakout forces required
- Settlement - consolidation
- Prediction of skidding and sliding

Table 1.1-2 Data requirements for S-SI analysis.

Soil Properties (required for all stratigraphic units)

- Noncohesive sediment
  - — Grain size (mm)
  - — Specific gravity and water content
  - — Bulk density
  - — Angle of internal friction (on effective stress basis obtained from direct shear or triaxial tests)
  - — Permeability
  - — Relative density
- Cohesive sediments
  - — Grain size (mm)
  - — Specific gravity and water content
  - — Atterberg limits (liquidity index)
  - — Bulk density
  - — Undrained shear strength (by miniature vane or unconfined compression - UU)
  - — Remolded strength/sensitivity
  - — Consolidation and permeability data
  - — Consolidated undrained shear strength (on effective stress basis with pore pressure measurements, CU - test)

Environmental Data (required for all sites)

- — Bottom slope
- — Wave climate and currents
- — Water depth
- — Water density (salinity)
- — Bottom roughness

Structure Data

- — Size, shape, and weight
- — Footprint/configuration/shape
- — Static and dynamic bearing pressure on footings (secondary vibrations)
- — Influence of structure on currents and waves around footings

In Situ Data

- — Cone penetrometer resistance
- — Pore pressures
- — Vane shear strengths
- — Resistivity/conductivity

(from Valent et al., 1988)

unreliable for critical Navy applications. Four fundamental S-SI processes, Shakedown, Skidding and Lateral Motion, Scour and Fill, and Dynamic Penetration, are identified in this report, and the related research issues recommended are directed toward gaining a fuller understanding of the basic mechanisms and environmental processes important in the dynamic coupling of the sea floor and an object (Figures 1 and 2). By definition, **Shakedown:** is a dynamic bearing capacity process due to cyclic loading by waves and currents (objects experiencing penetration under cyclic loading conditions [complex dynamic effects]); **Skidding and Lateral Motion**: is considered here for small normal loads when the object experiences lateral movement or skidding; **Scour and Fill:** removal and/or deposition of sediment around an object (static or in motion) that may experience burial or net transport; **Dynamic Penetration:** the dynamic penetration of an object into the seabed at various entry angles and velocities and the response of the sediment to deformation (stress and strain). Scientific issues and research thrusts are directed toward understanding the physics and modeling of the benthic boundary layer processes (with and without bottom sitting objects), time-dependent changes in the environment and sediment response, and their impact on the sea floor properties as they affect MCM operations.

Purpose... This report is a result of a one and a half day workshop on the subject of S-SI convened in Metairie, LA in November 1991. The meeting was attended by professional engineers and scientists from academia, government, and industry. Technical disciplines represented at the workshop included marine geology and geotechnique, sedimentology, oceanography, fluid dynamics and hydraulic engineering, signal processing, and physics and modeling, which provided a strong interdisciplinary forum. The purpose of the workshop was to identify important research issues that require additional research on the topic of S-SI in support of the Navy's Coastal Benthic Boundary Layer SRP. Names and affiliations of the participants who attended the S-SI workshop are included in Appendix A.

Organization of Workshop and Report... During initial deliberations on the topic of S-SI by the workshop attendees, the decision was made to organize the workshop into two technical groups to address interrelated but discipline oriented subject areas. Group One was identified as the Sediment Transport: Scour and Fill technical group and Group Two was the Geotechnical: Seabed Mechanics technical group. Members of each group are identified in Appendix B. Leaders were Steven Hughes, CERCWES, for the Sediment Transport group and James Hooper, Fugro-McClelland, for the Geotechnical group. The rationale for this division was for the purpose of focusing on specific technical issues by experts most closely associated with the required disciplines. Linkage and synergism between the two groups were maintained by regrouping

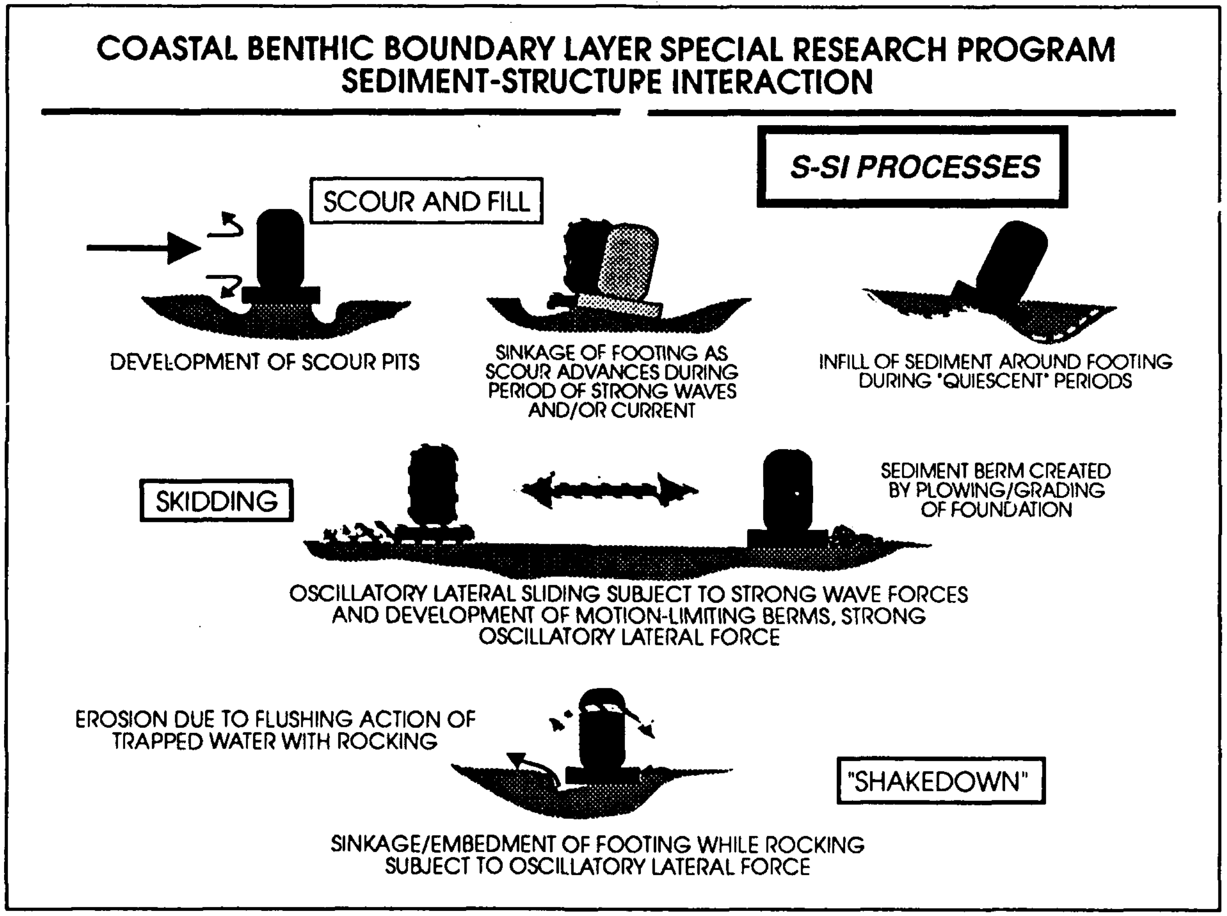
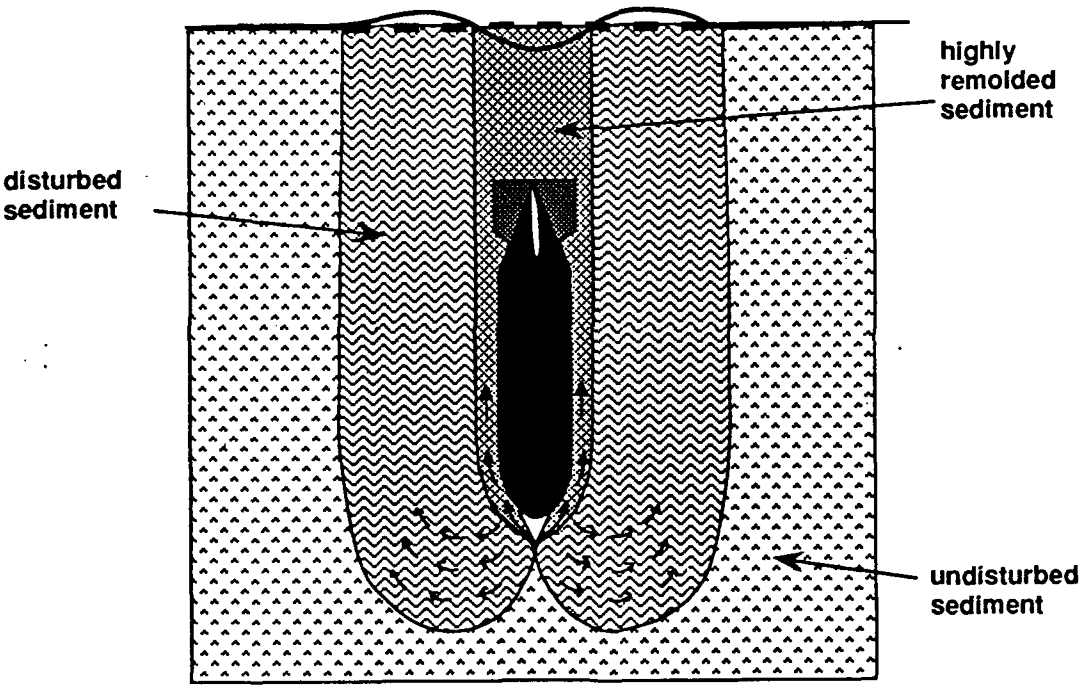


Figure 1. Sediment-structure interaction processes involving the coupling and dynamic interaction of an object and the seabed driven by complex environmental forces that vary with time. (Modified from Valent et al., 1988. Does not represent actual mine configurations; rather depicts particular sediment-structure interaction processes and mechanisms.)

COASTAL BENTHIC BOUNDARY LAYER SPECIAL RESEARCH PROGRAM

SEDIMENT-STRUCTURE INTERACTION



Picture of Penetrator

Figure 2. Sediment-structure interaction of an object penetrating the seabed, involving complex sediment remolding - deformation, pore pressure response and time-dependent changes in sediment properties. (Compliments of Phillip Valent)

all participants during the workshop to discuss technical issues identified by the two separate groups. Thus, this report is organized in two parts; recommendation for research in (1) Sediment Transport; Scour and Fill, and (2) Geotechnical: Seabed Mechanics. The methodology and organization proved successful and resulted in the recommendations identified in this report. It is anticipated that this report will provide a springboard for future research on the coastal marine environment in the important subject area of S-SI processes and mechanisms.

SEDIMENT TRANSPORT: SCOUR AND FILL

BACKGROUND

Seabed-Structure: Scour and Fill

Scour that occurs around a solid body resting on the sea floor, and the partial or complete subsequent burial of the body, is dependent upon the complex interaction of the fluid, sediment, and the solid body itself. These interactions include the turbulent hydrodynamic variation induced by the presence of the solid body in the flow, the transport of sediment by the flow, and the response of the sediment bed to the solid body surcharge (loading). Individually, these separate interactions are poorly understood, at best; taken collectively, the combined interactions of the scour process are virtually unknown. Consequently, reliable prediction of seabed scour around a solid body is beyond the current state-of-knowledge.

Fundamental research into the complex fluid/structure/sediment interaction is needed in order to improve our understanding of the scour problem to at least the same level as our present capability to specify the environmental forcing conditions. A crucial aspect of the problem of reliable S-SI predictive capabilities is a fundamental understanding of the nonlinear wave-current interactions and coupling with an object on the sea floor. Complex time-dependent interactions exist and reliable physical models are urgently needed.

The following list details those aspects of the solid body/scour problem where physical understanding and research are most needed. Several of these research issues are somewhat broad and encompass several separate topics that could be individually investigated. However, it will be important for individual efforts to be well coordinated within each of the research issues.

Research Issues:

1. What are the significant, time-dependent interactions between the small-scale, near-bed, wave boundary layer and the large-scale, benthic boundary layer?

2. How do suspended sediments affect the wave and benthic boundary layer? How does suspended sediment affect turbulence?

3. What is the role of dynamic pore pressures on sediment transport in the vicinity of a solid body resting on the sea floor? What are the time scales and transient phenomena driving and controlling pore water flow in proximity to the bottom sitting object?

4. How does the presence of a solid body impact spacial and temporal 3-D turbulent structure in the water column, and how does it affect the pressure distributions within the bed?

5. How can our understanding of the empirically based coupling between shear stress and sediment transport be improved? Specifically, what is the relationship between the spacial and temporal stress distribution in the wave boundary layer and the suspension and deposition of sediments?

6. How do large- and small-scale bedforms interact with the turbulent flow in the wave and benthic boundary layers?

7. What new methodologies must be developed in order to successfully apply advances in scour mechanics to practical applications?

8. New technology is required for the direct, nonintrusive, measurement of sediment transport in the field. Examples may include infrared optical backscatter sensors and ground penetrating radar.

9. Fluidization of a sandy sea floor: initiation of suspension under nonuniform and oscillatory flows. Effects of local gradients of density, sediment concentration, velocity, pressure and stresses due to waves, turbulence and to the presence of a structure. Possible extension of granular flow mechanics to the dynamics of bedload transport under oscillation and nonuniform flow conditions. Theoretical and experimental advances are needed beyond Meyer-Peter formula for sediment transport rate in steady flows. Collisions among particles are accounted for (S.A. Savage, McGill, and Jim Jenkins, Cornell).

10. Effects of suspended sediments on the structure of the turbulent boundary layer (turbulence intensity variation, vertical structure of Reynolds stresses).

11. The role of large scale (vertical and horizontal) variations on the benthic boundary layer and on the sediment motion within. The large scales may correspond to Ekman boundary layer depth, wavelength of the water wave, or the sandbars. Understanding of the three dimensional structure (velocity and stress) in the wave boundary layer over sandbars or irregular bathymetry is needed and the mechanics of sandbar formation and migration due to large scale variations of boundary layers needs to be more fully understood.

12. Sediment instability, formation and migration of ripples: ripples are due to unstable sand motion under oscillatory flows and are a major source of bottom roughness. Given the amplitude and frequency of an oscillatory flow outside the boundary layer and the grain size, what are the likely sand-ripple wavelengths and ripple heights? How does the role of vortices in the boundary layer affect ripple development? How do the vortices affect scour at the object/sediment-water interface? How is orbital wave particle dynamics in the benthic boundary layer affected by the presence of an object on the sea floor? How do large scale horizontal gradients in the boundary layer, due to a structure of surface waves of the order of 100 m, affect ripple development and migration? How do ripples on large bars develop and affect the formation and movement of the bars?

13. Dynamics of cohesive sediments in and below the wave boundary layer.
    A. Fluidization of cohesive seabed
    B. Bulk motion of fluid mud due to nonuniform gradient and transients.
    C. Instability of a muddy seabed, with or without a structure.
    D. Non-Newtonian rheological behavior of fluid mud.
    E. Time-dependent response of sediment pore water pressure as a function of surface wave activity and the response of pore pressure as a function of the combined effects sediment-structure dynamics and surface wave activity. These processes are poorly understood especially for complex sediment types with admixtures of sand, silt, and clay that are common in the marine coastal environments.

    F. Dynamic behavior and properties of soft mud possessing total organic contents of greater than 2% (>2% TOC). Rheological behavior, cohesion, compressibility, physical properties, erodibility, etc., in relation to depositional environment, sediment type, mineralogy, and microfabric.

GEOTECHNICAL: SEABED MECHANICS

BACKGROUND

Geotechnical: S-SI, Properties, and Sensing Methods

The mechanics of Sediment(seabed)-Structure Interaction phenomena are poorly understood particularly with regard to the coupling processes and mechanisms and time-dependent changes in the seabed as a function of the dynamics of the sediment-structure system and the energy of the environment. The processes and mechanisms are complex and additional research is required to develop reliable predictive capabilities for the response of objects coupled with the sea floor.

Important research areas of investigation that would improve modeling and predictive capabilities include factors such as scaling effects, penetration rate functions, dynamic forces, coupling phenomena, and strength degradation effects and the significance of these factors on the analyses of penetration, sinkage, sediment liquefaction and pumping, and punch-through. Punch-through is a problem in layered sediments where the bearing resistance of a stiff surficial layer is exceeded and the object "punches through" into a soft underlying layer. These geological conditions can occur in coastal environments and are a result of changing environmental conditions and changes in source material. The physics and modeling of dynamic penetration of objects into the seabed is another area where research is required and has particular importance to problems in mine warfare. Reliable models for layered sediments are sorely needed particularly in cases of punch-through and dynamic penetration of objects in seabed sediments.

An important topic of research related to Sediment(seabed)-Structure Interaction is in the area of object sensing methods and detection of structures on and buried within the seabed. New technologies that offer rapid means of detection with high resolution are crucial to Naval applications.

Three broad technical areas were discussed by the Geotechnical Group and research recommendations and issues were identified. The three areas included, (1) Sediment(seabed)-Structure Interaction, (2) Sediment Properties and Processes, and (3) Object Sensing Methods. Object Sensing Methods will be covered in greater detail in another SRP workshop, but the topic is covered briefly here because of its importance to S-SI processes and technical issues.

gassy sediment); different sediment types, environments, and wave loading. Attenuation of pressure signal with subbottom depth and time-dependent changes in excess pore pressure.

5. Pore pressure in Oxidation/Reduction zones caused by microbiological activity and in gassy sediment.
6. Degradation of vessel signatures by sediment; Change in neutralization explosion pressure in sediments.
7. Thermal signal properties of geological materials.

Measurements of Sediment Properties and Data Analysis:

1. Determination of sediment properties
   a. Using surface shear waves.
   b. Tools and analysis methods for resistivity of fine-layered sediments (probe).
   c. Tools and analysis for thermal pulse method for sediment classification and detection.
2. Classification of sediment properties by side scan sonar; estimation of sediment properties (geotechnical) by other remote detection methods.
3. Perceptual science (i.e., artificial intelligence) to characterize sea floor properties.
4. Tomography for data correlation.

III. Object Sensing Methods (Detect/Classification)

Research Issues:

1. Detection of objects with properties similar to sediment properties.
2. Diffraction pattern recognition of objects.
3. Discrimination of objects on sea floor.
4. Multimode scanning of objects.
5. Rapid rate of areal coverage.
6. Discrimination of manmade vs. natural objects.
7. Exploitable penetrating radiation.
8. Detection of objects by shear wave propagation.
9. Cataloging of object signatures in various sediments.

I. Sediment-Structure Interaction

Research Issues:

1. Prediction of threshold loading for gap formation.
2. Prediction of object/sediment/fluid interaction for cohesive sediments (in particular at gap between sediment and object).

   On a clayey (mud) sea floor:
   a. Burial of a structure into the soft bed by self weight. Large amplitude nonlinear deformation.
   b. Wave-induced sediment deformation stresses and pressure when the structure is allowed to move (sway, heave, rock, etc.). Nonlinear constitutive behavior of clayey sediment should be considered (under undrained condition).
   c. Current-induced stress and pore pressure and sediment deformation in a nonlinear sediment.
3. Prediction of skidding vs. sinking (gouging).
4. Development of excess pore pressure under dynamic loading (local effects).
5. Dynamic sediment–rheology/viscoelastic wave-structure interaction.
6. Evaluation of forcing function and dynamics on seabed objects.
7. Self-weight sinkage-static and dynamic loading.
8. Effect of gassy sediments on sinking.
9. Object implanting by bioturbation.
10. Develop modeling laws for scaling (lab to field).
11. Modeling variations of engineering properties of sea floor sediments; evaluate their effects/influence on S-SI.
12. Prediction of fluid/sediment structure interaction (cohesionless sediment)
13. Refine analytical models for projectile penetration. Dynamics of penetration of mine into a viscoelastic sediment.

II. Sediment Properties and Processes

Research Issues:

1. Bioturbation effects on material types and on micro and macro variability of properties.
2. Diagenesis is a process and important factor in the lateral and vertical variability of sediments and it is important in cement types and effects on sediment properties. Processes are poorly understood in relationship to environments of deposition, various sediment types and oxic and anoxic environments.
3. Gas/Sediment compressibility/strength/moduli; Gas bubble mobility in soft clay/loose sand.
4. Excess pore pressures under dynamic loading (including

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Appendix A

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TECHNICAL WORKING GROUPS

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Interactions between Environmental Processes at the Seabed and High-Frequency Acoustics: Workshop Recommendations

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1. Statement of the Problem

We took as our problem the prediction of acoustic propagation,including attenuation and scattering for surficial, nearshore marine sediments. Because predictions are scarce and results to date are not entirely in agreement, of particular interest is the propagation and scattering of sound incident on the bottom at low grazing angles. The frequency range of interest was bracketed very broadly as 1-500 kHz, with the surficial 10 m and especially the top 1 m of sediments being of prime concern. Water depths considered extended from the outer edge of the surf zone to roughly 100 m.

Better understanding of this problem demands interdependent research in several disciplines. This research must combine analysis and measurement. Its end result would be an hierarchy of modeling including

- Acoustic models: Mathematical techniques and approximations yield predictions for acoustic propagation and scattering based on assumptions regarding sediment composition and morphology.

- State models of sediment physical properties: Considerable research is required to improve knowledge of sediment properties relevant to high-frequency acoustics. These models provide inputs for the acoustic models.
- Environmental process models: Hydrodynamic, chemical, and biological processes create and transform the features described by the sediment models. An understanding of these processes would allow prediction of acoustic behavior (via the state models) without intensive or extensive measurement of sediment physical properties.

2. The Central Role of Sedimentary Physical Properties

Theories for acoustic propagation and scattering have progressed from the simplest models that approximate the benthic boundary layer as a set of flat, lossless fluid layers to the present collection of models that include full wave solutions of propagation through visco-elastic solid layers and predictions of scattering from interfacial roughness represented by wavenumber spectra. Many of these models have not been subjected to rigorous experimental tests, owing largely to the lack of combined measurements of acoustic and physical properties. Experimental data that have been gathered over the past ten years show that there remain significant gaps both in understanding of the relevant acoustic and physical processes and in the predictive capabilities of the present collection of models.

Following the hierarchy defined above, one may ask whether the failure of present acoustic models is due to inappropriate use of mathematical approximations or to inaccurate modeling of sediment physical properties. While the answer to the first question is in some doubt, there seems little doubt that present models for sedimentary physical properties are oversimplified. For example, is it valid to make the assumption that the ocean sediment is a layered elastic solid, when it is in fact porous? In reexamining the current models and their underlying assumptions, and in the development of new models, the role of sedimentary physical properties is central.

It is clear that deterministic or stochastic calculation of the propagation of high-frequency sound into and through sediments requires quantitative description at 1-cm resolution or finer of those physical properties that can change sound propagation (direction or magnitude). Measured statistics for these properties must include, at minimum, the mean and spatial covariance. Routine measurement of sediment properties on these scales is not feasible. We agreed that it would be most practical, therefore, to predict acoustically relevant physical structure of surficial sediments from knowledge of environmental processes. A short list of the relevant parameters includes density (with temperature and salinity contributions), microtopography, porosity, permeability (and associated flow parameters such as tortuosity, pore size, or microstructure), complex bulk modulus, complex shear modulus, frame bulk modulus (including cementation effects), and the shapes and sizes of any included gas bubbles. The importance of these parameters stems from their roles in determining the partitioning of acoustic energy:

Total acoustic energy = Transmitted + Absorbed + Scattered

3. Environmental control of acoustically relevant physical parameters

Environmental processes govern both the composition and morphology of sediments and so determine the geoacoustic properties of interest. Bottom topography from the 1-m scale downward is controlled by a combination of physical and biological processes that differ with both location and time. Organisms by feeding and excavating create mounds of up to 1 m diameter and feeding pits of up to 10 m diameter. Combined effects of schooling animals can be particularly dramatic, with schools of skates and rays in warm temperate to tropical environments being able to change the topography within an embayment from a smooth seafloor to one with pocks of 30 cm diameter overnight. At high latitudes, grey whales and walruses can cause similarly dramatic changes of topography (Nelson et al. 1987).

Microtopography must be considered the equilibrium or (in the case of unsteady biological or physical processes) disequilibrium result of production and destruction. The rapidity of approach to equilibrium has not been widely appreciated. Animals can return a storm-smoothed site to equilibrium, centimeter-scale roughness in 10 d or less (Wheatcroft et al. 1989). At shelf depths, hot spots of biogenic sediment movement can come and go within a few days. What sets the time scale for equilibration is tracking by surface-active organisms as well as the recently elucidated process of horizontal mixing (Wheatcroft et al. 1990, Wheatcroft 1991). Except for some correlation with bedform periodicity (Eckman 1979; Hogue and Miller 1981) and a few other exceptions, the usual trend is for rapid decorrelation of abundance with separation distance in animal populations (e.g., Jumars 1978). An important caveat, however, is that the data are very gappy, making even strong autocorrelation easy to miss (Jumars and Eckman 1983). Abundance of any one species per unit of area (and thus presumably of the structures that organisms produce) from widely scattered samples within one environment typically shows greater variation than would be expected from a Poisson distribution. Higher moments have not been well explored, but the mean and variance of abundance per sample of fixed size usually are related as $s^2 = 1.64\,(\bar{x})^{1.2}$ (Vézina 1988).

Surface microtopography also has secondary effects. Negative relief features collect flocculent particles (Thistle 1981; Aller and Aller 1986) that locally will reduce the gradient in density between overlying water and the seabed. Migration of wave- and current-produced bedforms buries such flocculent accumulations and results in lenticular inclusions within the sediment fabric that affect acoustic propagation. Shell lag layers are generated by the migration of sand ripples and subsequent burial of coarse shell hash that has collected in ripple troughs. Shell lags are significant sound scatterers for reasons related to density inhomogeneities both intrinsic and extrinsic to shells. Despite the porous nature of weathered carbonate shells and the similar density of carbonate shells to quartz sand (2.70 vs 2.65 g cm^{-3}), the shells are nevertheless denser than the saturated sediments surrounding them. Conversely, the presence of buried shells can reduce bulk density of sediments by creating water-filled voids between the coarse shells. In some cases these voids may be filled with fine sediment derived from settling of suspended sediment load after storms. The ability of buried carbonate shells and tests to affect compressional wave transmission through sediments has been demonstrated numerous times (Richardson 1986; Stanic et al. 1989). Migration of sand ripples may create discontinuities in the sediment fabric in the absence of coarse lags by sorting of sediment into planar bottomset laminae and dipping foreset

and stoss-side laminae (Reineck and Singh 1980). If the internal structure of asymmetrical ripples is preserved, the resultant buried features may provide discontinuities that could display enough of a density difference to create volume scattering. Despite the periodicity imposed by wave- and current-produced bedforms, sub-1-m microtopography characteristically shows a red power spectrum of variation in height (Briggs 1989).

A second biotic influence on and beyond the interface is the provision of conduits for high-frequency sound. Abundant macroscopic animals of the sedimentary seabed fall into two major categories, suspension and deposit feeders. The former are relatively sedentary because boundary-layer flow is much more effective than benthic animal movement in supplying suspended food. Their abundance will depend upon local concentration and horizontal flux of suspended organic matter. Hence they often are associated with coarser sediments in areas where phytoplankton blooms are frequent and intense. A bivalve is an example of this ubiquitous feeding guild. The feeding siphon of order 1 cm in diameter reaches to the sediment-water interface and connects to the shell-encased body and in some cases to a vertical feeding burrow. Deposit feeders, on the other hand, normally increase in abundance with decreasing grain size, reflecting a dependence on grain-surface-associated food and ultimately a dependence upon vertical flux or combined horizontal and vertical flux. They maintain a respiratory connection of some sort, often a vertical tube or burrow, with the interface. A characteristic shallow subtidal abundance of macroscopic animals is 10^3 m^{-2}, though local abundances can rise at least two orders of magnitude higher. The bottom, then, contains about 10^3 millimeter-scale openings m^{-2} from a few centimeters below the interface to the interface. One opening of centimeter size m^{-2} is characteristic, though two orders of magnitude higher abundance of these larger openings may be seen in dense communities. The surface opening of a tube or burrow may or may not be elevated above the surrounding sediment. The vertical extent of the centimeter-scale openings produced by burrowing shrimp may exceed 2 m in depth where buried organic deposits are rich (Pemberton et al. 1976; Tedesco and Wanless 1991).

At the millimeter scale and both on and in the seabed, organisms influence the structure of grain-to-grain contacts by feeding on the sediment and producing fecal pellets. The fraction of sediments in the surface few centimeters that are contained in recognizable fecal pellets range from near zero to 80% or even more. This packaging affects not only porosity and permeability, but also the frame bulk modulus. Virtually all sediment grains are coated with bacteria (Dales 1974), whose viscoelastic exopolymer secretions may also play a major role in mediating grain-grain friction and hence acoustic attenuation. At the macroscopic level, there is some debate whether a sediment is better described as a granular mixture or as a gel with grain inclusions (Watling 1988).

Just as with surface roughness, organisms and physical processes are responsible for both creating and destroying volume heterogeneities within surficial deposits. A physically controlled end member is the hummocky cross stratification characteristic of storm-dominated shelves (Dott and Bourgeois 1982; Duke 1985). Rapidly time-varying flow directions and intensities generate lens-like features of varying grain size, producing volume heterogeneities of 10- and 1-cm extent in horizontal and vertical dimensions, respectively. Volume heterogeneities are evident in any X-radiograph from sediments inhabited by animals. They comprise the animals themselves, the aforementioned burrows and shell debris, among other features. While often described from X-radiographs, this heterogeneity and its anisotropy have never been quantified; modern scanning densitometry is well suited to this task. Differences in bulk density reflect differences in sediment porosity that may be depicted by high-resolution electrical resistivity core imagery (Jackson et al.

1991). Current- and animal-produced (Rhoads and Cande 1967; Cadée 1976) layering by grain size also affects acoustic propagation as it does X-ray transmission. Biogenic graded bedding and lag layers can be expected anywhere where grain size shows substantial variance and sediments include enough material to support deposit feeders.

Superimposed on this physical-biological framework and dominant in areas of low physical energy and low or missing oxygen (e.g., deeper regions of some harbors) are geochemically produced heterogeneities. Notable are methane bubbles. Bacteria exhaust oxidants in the sequence of decreasing energetic gain, i.e., O_2, NO_3^-, MnO_2, FeOOH, SO_4^{2-}. The end products of the reactions of these oxidants with organic matter are either soluble or not very abundant. When these electron acceptors are exhausted, however, methanogenesis usually commences. Production in coastal sediments can reach levels that lead to gas bubble formation and ebullition (Martens 1982). This process will be most intense where particulate organic inputs are rapid and the above-listed oxidants are scarce. Knowledge of bottom-water O_2 content and rates of organic deposition can be used to predict the sediment depth and magnitude of methanogenesis. This depth will also be influenced by the penetration of the above-mentioned tubes and burrows, but this effect already has been successfully modeled. Extant theory, however, has not explored the factors controlling the size-frequency distribution of methane bubbles in sediments. A completely unexplored effect is the potential for production of oxygen bubbles by microscopic plants that inhabit surficial grain layers.

Interstitial water geochemistry influences sediment physical properties by either enhancing cementation or impeding particle-particle interaction, depending on the concentration of reactive pore-water solutes. In shallow marine environments, seawater is often supersaturated with calcium carbonate, and interstitial precipitation of carbonate is common. In the case of restricted basins where pH (i.e., pCO_2) can fluctuate greatly, dissolution weakens and erodes carbonate cementation. Moreover, benthic organisms affect the diagenetic reactions taking place within the surficial sediments by controlling pore-water composition. Burrowing infauna, by intensive reworking of sediment and creation and maintenance of tubes and burrows, irrigate surficial sediments. Dilution of supersaturated pore waters in carbonate sediments by burrow irrigation and the physical separation of particles by bioturbation inhibit cementation of carbonate particles. The construction of tubes by burrowing infauna, however, often results in binding sediment into structures that are potential scatterers of acoustic energy.

Preservation of deposited organic matter affects the sediment physical properties in nearshore areas of high organic input such as bays, harbors, and lagoons. High amounts of organic material in relation to the amounts of minerals in the sediment depresses the sediment bulk density and shear modulus (Briggs 1991). Storage of diagenetic products of decomposition (NH_4^+, NO_3^-) is proportionately greater in regions of rapid sedimentation and low biological activity compared to regions of higher reworking by benthic organisms (Aller and Mackin 1984). Fine-grained sediments, especially clays, are highly susceptible to binding of these ions and, thus, likely to undergo geochemically mediated consolidation. Vertical post-depositional migration of several redox-sensitive elements (Mn, Co, Ni, Cu, Fe, and U) within the sediment is a result of changing depth-dependent Eh conditions. Decrease in Eh as a consequence of organic carbon oxidation causes a concentration of Fe^{2+} that can result in intensive changes in sediment porosity due to accelerated dewatering (Briggs et al. 1985). Presence of burrowing infauna tends to interrupt or prevent this exclusion of water from the sediment matrix (Richardson et al. 1985).

An interesting side issue is the effect that a large, wholly or partially buried object will have on the immediately surrounding seabed in terms of modulating all these factors. A partially buried object will become a substratum for attachment of biota whose by-products will locally enrich the deposit. A buried or partially buried object will impede the downward diffusion of oxidants unless it sets up a pressure imbalance in interstitial fluid as currents pass over. The biological and geochemical environment where the object contacts the surrounding seabed thus may be modified substantially over the ambient condition.

4. Status of acoustic modeling

This level of environmental detail has not yet been incorporated into routine modeling of high-frequency acoustic propagation into and through the seabed. There are few explicit applications of theory to the problem of propagation of high-frequency sound into the seabed, especially at low grazing angles. Nonetheless, there are strong indications that simple theories that do not take the above-documented environmental complexity into account have failed to explain observed phenomena.

For example, there is scientific debate at present relating to the depth and angle of penetration of acoustic energy and its backscatter from regions of the bottom beyond the critical grazing angle. In theoretical treatments of this problem, it has been assumed that the sediment may be modeled as a viscoelastic solid. Several experiments have been performed to attempt to verify this assumption. Measurements of acoustic pressure contours by Williams et al. (1989) are notable for their quality and detail. Upon direct comparison of the measured contours with viscoelastic model predictions (SAFARI) one can confirm that there is agreement at steep angles of incidence. However, at incidence angles larger than the critical angle, there is lack of agreement in detail (Fig. 1). Altenburg, Chotiros and Faulkner (1991), in an in-situ experiment using an array of buried acoustic sensors in which the direction and speed of the detected sediment acoustic wave were computed, reported that acoustic waves entering a sandy sediment appear to refract into waves traveling at two different speeds, depending on the angle of incidence. At steep angles, the wave speed was consistent with that measured from core samples, but at shallow angles a slower wave speed was found. The data of Fig. 1 may support this result, as there is an indication of anomalously steep refraction, as would occur for a slow wave. These results indicate that existing propagation models, based on the viscoelastic solid assumption may not incorporate enough of the essential physics to reproduce all the effects seen in experiments. Well controlled, "benchmark" tank experiments should be defined that allow examination of these issues in an idealized homogeneous environment.

It is possible that excess penetration, if it exists, is due to the porous nature of the sediment. A large literature exists on the Biot-Stoll model for propagation of sound in porous, fluid-filled media, but most of this work has been motivated by low-frequency applications (Stoll 1974; Stoll and Kahn 1981; Yamamoto 1983; Yamamoto and Turgut 1988). The relevance of this model or improved variants to high-frequency propagation in coastal sediments must be determined.

Acoustic models may be either stochastic or deterministic. Stochastic models make predictions of statistical quantities such as second and higher moments of the propagated or scattered field. These field moments are, in turn, determined by moments describing random

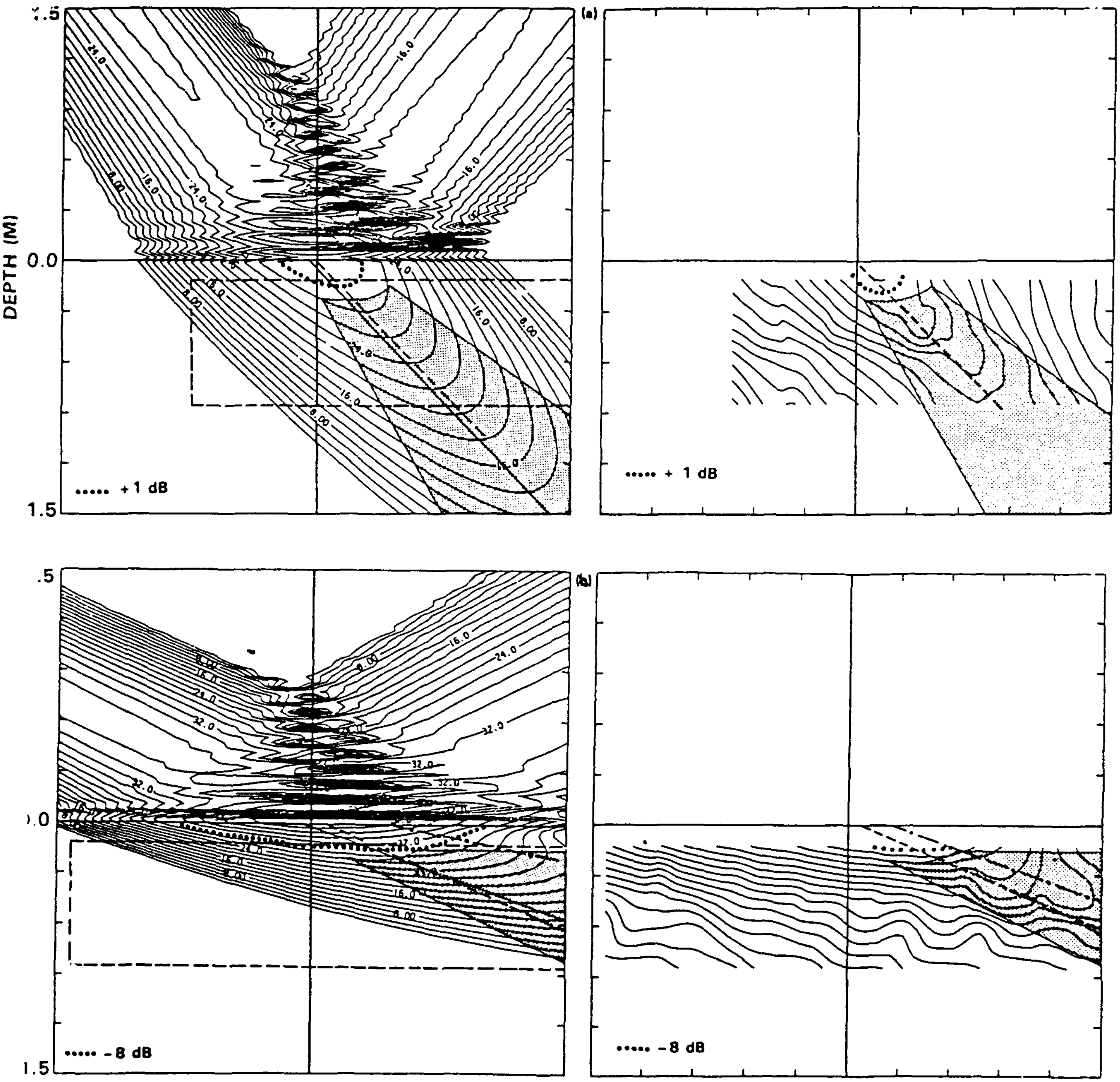

Fig. 1 Comparison of predictions (Left) and measurement (Right) of sonar beam transmission through a water-sand interface (Williams et al. 1989). The incident grazing angles are 51.9° (Upper) and 25.8° (Lower). The latter angle is equal to the critical angle, for which sound is refracted horizontally. The shading indicates the region in which comparisons of prediction and measurement are considered valid. Comparison of contour lines in this region for the two lower figures suggests that acoustic energy penetrates the bottom at a steeper angle than predicted.

roughness and heterogeneity. A good example is the perturbation treatment of volume scattering, in which the second moment of the scattered field (the average intensity) is determined by the second moments of material properties such as density and compressibility. Deterministic models lend themselves to simple, non-random environments, but they may also be applied to complicated cases, and Monte Carlo methods can be used to estimate statistics.

Stochastic models for scattering of sound from bed roughness have been formulated and tested with encouraging results (Jackson, Winebrenner and Ishimaru 1986; Stanic et al. 1988, 1989; Jackson and Briggs, in review), but these tests were made for underdetermined environments. It appears that lowest-order perturbation theory may provide a useful description of scattering at small grazing angles, provided that roughness is not too great and provided that the sediment can be treated as either a fluid (Kuo 1964) or elastic solid (Dacol and Berman 1988; Kuperman and Schmidt 1986). The stochastic roughness scattering problem has not yet been formulated for more realistic sediment models (e.g., the Biot-Stoll model) although Sammelmann (May 1991, June 1991) has applied the Biot-Stoll model to the rough under-ice surface.

Most treatments of roughness scattering (including many of the references given in the previous paragraph) assume that bottom relief is a Gaussian random process. This assumption has not yet been tested. It is clear that the Gaussian assumption fails to some degree: cusp-like sand ripples cannot be described by a Gaussian random process. The real question is whether non-Gaussian features of bed roughness lead to significant departures from the predictions of acoustic models that assume Gaussian roughness statistics. Some acoustic models treat bottom roughness as fractal (Jackson, Winebrenner and Ishimaru 1986) having no intrinsic correlation length or vertical relief scale. Other models (Stanton 1984, 1985) treat roughness as non-fractal with well-defined correlation and relief scales. Both approaches are idealizations of reality. Which idealization best captures the features of acoustic significance?

Existing stochastic models for sound scattering from sediment inhomogeneities (Hines 1990; Tang 1991) also employ lowest-order perturbation theory. High levels of sediment volume scattering are indicated by scattering data obtained at silty sites (Mourad and Jackson 1989; Jackson and Briggs, in review), but rigorous model-data comparisons are impossible owing to the lack of statistical data on sediment inhomogeneity. Even the crudest data are lacking, much less information on whether Gaussian or fractal models are useful. Finally, it should be noted that models for sediment volume scattering treat the sediment as a fluid and do not attempt to take account of its elastic properties or porosity.

Lowest-order perturbation theory as applied to either interface or volume scattering is an example of a single-scattering formalism. It is an open question whether one of the many extant multiple scattering formalisms should supplant perturbation theory as a model for sound scattering by coastal sediments.

Insight into the physical mechanisms of scattering can be addressed by using numerically intensive "exact" formulations (Thorsos 1986, 1988, 1990; Thorsos and Jackson 1989, 1991; Stephen 1983, 1984, 1988; Virieux 1986). These methods can treat rough surfaces and volume heterogeneities in vertical cross sections through the seafloor. The dimensions of the scatterers can be of the same order as the wavelength of the incident field. All propagation effects including shear waves, interface waves, two-way propagation, and multiple interactions between scatterers are considered. These methods have been used specifically to address low grazing angle scatter in the frequency band 50-500 Hz in the Acoustic Reverberation SRP, and the numerical formulation

can be scaled to treat the higher frequency regime of this program (1 kHz-500 kHz). The methods can be extended to consider intrinsic attenuation, propagation in Biot media, and propagation in solids and (or) fluids with gas inclusions. Used with Monte Carlo techniques, the exact methods can provide tests of approximate stochastic models, if both are applied to tractable 2-D benchmark problems.

In addition to the interaction of the above environmental heterogeneities with compressional waves, some other acoustic phenomena may need attention. One is acoustic tunneling (Stephen and Bolmer 1985) and the related interactions and potential mode transformations among compressional waves, shear waves and interface waves. The existence of interface waves needs evaluation for the high frequencies under consideration. It is becoming clear that one cannot deduce acoustic behavior at one frequency by simple geometric scaling from other frequencies. Laws for proper dynamic scaling of heterogeneous, multiphasic (solid-liquid-gas) media like those of natural sediments are not yet established.

5. Environmental instrumentation required

It is clear that one can decide which acoustic model is best and can evaluate its strengths and weaknesses (i.e., the need for further model development) only by achieving more-than-adequate resolution of the sedimentary physical parameters that affect sound propagation. There was unanimous agreement to focus on in situ approaches less prone to artifact than core retrieval and post processing. Sorely needed, for example, are methods with higher spatial resolution and more rapid measurement capabilities than standard coring to establish water content. Prime candidates include electrical conductivity measurements for determining aspects of permeability and porosity. While such methods are used routinely by geochemists, evaluation of the calibration factors in a range of naturally complex sediments should serve to make them more useful. These new (to shallow-water acoustics) methodologies should be supplemented with established technologies, e.g., Coulter counting, microscopy and settling tube approaches to establishing disaggregated grain sizes.

The possibility of in situ X-radiography along the lines of the Rhoads-Cande (1971) interface (guillotine) camera system should be explored. Particular attention should be taken to resolving size distributions of gas bubbles. Images obtained should be subjected to modern image analytic methods (e.g., scanning densitometry) to extract information (e.g., autocorrelation length scales for porosity) of interest in acoustic modeling and in testing environmental models that predict these physical parameters from knowledge of environmental processes producing them. Rheological data from in situ devices such as duomorph sensors (Lavoie and Anderson 1991) as well as geoacoustic probes (Barbagelata et al. 1991) need similar analysis. Prospects for acoustic tomography of sediments, with due recognition of the limits set by scattering and signal processing, need realistic evaluation. It should be noted that tomographic inversion depends on the use of accurate acoustic models, whose development is one of the chief goals of this program. Thus, tomographic methods may be considered as research topics, rather than standard tools, at least in the first experiments.

Means need to be sought to automate stereophotogrammetric (Briggs 1989) and acoustic (Igarashi and Allman 1982, Damman and Lauter 1987) collection of microtopographic data.

Thought should be given to developing some means, independent of acoustic inversion, of estimating the frame bulk modulus of Biot-Stoll formulation (Stoll 1974).

Nonlinear acoustic characteristics of bubbles should be explored as an in-situ method of estimating trapped bubble populations. It is one of the few approaches that can distinguish bubbles from other scatterers in the sediment, such as shell fragments and sediment grain size or density inhomogeneities. It has the advantage of being a remote sensing method, with much larger area coverage than in-situ X-radiography. The two methods can be complementary: X-radiography may be used to obtain precise ground truth at selected points, which can then be used to calibrate a nonlinear acoustic survey of bubbles over a whole test site.

6. Acoustic instrumentation required

Acoustic instrumentation must be sufficient to separate surface transmission and scattering from volume propagation and scattering. This separation requires use of transmitters and receivers both in the water column and in the sediment. Generally speaking, it is possible to obtain a synoptic view using acoustic instrumentation placed in the water column, while buried instrumentation provides a more intensive view with higher resolution. Environmentally induced scattering of sound is a stochastic process, and careful consideration must be given to the difficult problem of obtaining an adequate statistical sample with apparatus that is essentially fixed.

A knowledge of the sound field in the bottom can give insight into the important mechanisms responsible for the scattered field in the water. Scattering in elastic media, however, excites shear waves and interface waves in the bottom that are not treated in a purely acoustic formulation. It is not clear how a hydrophone, which is designed to respond to an omni-directional force, responds to the elastic field in the bottom, where principal stresses are not equal and shear stresses are present. The inclusion of buried three-component accelerometers in our lab and field tests should be considered in order to distinguish the contributions to the scattered field from the different wave types. Shear and interface wave effects must also be included in the theory. For Biot media, the distinction between a hydrophone, which may respond to pore pressure fluctuations, and accelerometers, which may respond to the frame motion, is particularly important.

It is clear that a variety of sediment acoustic and shear probes will be needed to estimate sound velocity, attenuation, dispersion, volume scattering and time and frequency spreading. Such probe arrays are also needed to explore tomographic methods. Analogously a variety (in waveform, signal type and frequency) of sound sources will be needed. We anticipate extensive reliance on both theory and empirical findings from signal processing studies.

Monostatic source-receiver arrays in the water column should have tilt-and-rotate freedom to deal with three-dimensional environmental heterogeneity. Bistatic approaches to acoustic measurements in the water column also should be used, although there is a difficulty in obtaining adjustable geometry. Simple mine-like targets and implanters should accompany the acoustic measurements, especially for what they can reveal about acoustic coupling to buried objects.

7. Experimental design

As noted above, several important acoustic models await experimental verification. These models may be regarded as hypotheses to be tested, and, as such, they provide an initial framework for experimental design. At the same time, we realize that there are large gaps in modeling, i.e., that new hypotheses will be formulated as the study proceeds. The trick in experimental design is to develop models and measurements apace with an understanding of mechanisms. Trying to work faster hides phenomena in fitted but poorly understood coefficients, in grossly underdetermined physical systems or in both. We despair of achieving predictive ability of acoustic propagation from knowledge of environmental processes alone. Thus we envision a two-step development of predictive theory — prediction of sedimentary properties from knowledge of environmental process and prediction of acoustic propagation from knowledge of sedimentary properties. The central role of sedimentary properties requires their sufficient resolution to test both competing environmental models and competing acoustic models. To achieve overall predictability and realize maximally any potential for generalizing from environment to environment, we endorse a "team" approach in which the majority of environmental and acoustic modelers and measurers are involved in each laboratory and field effort.

Both laboratory tank experiments and field experiments are endorsed. Tank experiments offer control while field experiments offer realism. On the negative side, tank experiments are strongly constrained in geometry owing to the proximity of reflecting and scattering boundaries, and field experiments may suffer the curse of unrepeatability.

Toward a paced elucidation of mechanisms, we propose a benchmark experiment in a laboratory tank, filled with sand made horizontally and vertically uniform. The idea is to eliminate as much of the normal, environmental process-imposed heterogeneity as possible. High-resolution measurements of sedimentary properties in this setting are at least as important as in subsequent field efforts both to calibrate devices against each other for later field application and to establish the degree of homogeneity achieved. It is essential, for example, to control and quantify microbial coatings on grains and the distribution of gas bubbles in the experimental tank. The primary question is the propagation of acoustic energy incident at low grazing angles. Is propagation as expected for fluid, viscoelastic, or porous media, or are other models needed?

It is essential to measure the amount of energy penetrating the bed, including the possibilities of tunneling and mode conversion. First experiments should deal with a bed that is flat above the length scale of sediment grains, though experimental interface roughening in subsequent experiments also would be informative. Distribution of absorption between viscous damping and grain-grain friction (and bubble absorption, if any) should be evaluated for comparison to model prediction. Likewise, the partitioning of scattering among intrinsic grain roughness, mode conversion, and measured bulk heterogeneities needs to be evaluated to establish goodness of fit to extant models and the need for new models.

The sand tank experiment can provide test and calibration of some of the apparatus to be used in field experiments, notably probe systems for intensive measurement of sediment properties and for measurement of the acoustic field. The tank environment is also ideal for first tests of tomographic methods, as simple, controlled heterogeneities can be established.

The first field experiment should be conducted in a natural but still comparatively uniform environment. Logistical convenience (e.g., off the end of a pier) and a background of environmental information are two important site-selection criteria. Water depth must be sufficient to avoid unwanted scattering and reflection from the ocean surface. The primary questions are two: Can environmental models in hand predict the measured sedimentary heterogeneity, and can the surviving acoustic models predict propagation and scattering from the data base of measured environmental parameters?

In parallel but not necessarily perfectly in phase with this "field sand" experiment will be conducted a series of laboratory "mud tank" experiments. Consensus was reached that perfect reproduction of field conditions in muds was neither possible nor desirable, not least because proper scaling laws for acoustic propagation through heterogeneous media are not established. The *sine qua non* of a good laboratory experiment is reproducibility and sufficient simplicity that lack of fit to prediction can be interpreted unambiguously as a fault of either the prediction or the physical realization. In short, the purpose of a laboratory experiment is to link cause and effect unambiguously. It thus makes little sense to work with complex, seemingly more natural muds until geoacoustic behavior of simple, reproducible mixtures is understood. Once again overdetermination of the physical properties of the contained sediments thus is highly desirable. Analogous to the sand tank experiment, the primary acoustic issue is propagation in homogeneous muds. Additional research issues include effects of microbial coverings, grain-size mixtures, mixtures of varying expendability (mineralogy) or bubble inclusions, among many others. Explicit selection of laboratory variables awaits the results of laboratory tests with simpler sands.

The combination of the laboratory sand- and mud-tank experiments, together with the field experience at a sand site is designed to allow the planning of a field experiment on a natural mud in a harbor or harbor-like setting. The idea is to go a small enough number of levels beyond the complexity of the laboratory and the sand field site to retain a grasp of physical mechanisms determining the results. One simplification attainable at organically rich sites of limited water circulation is that seasonally anoxic waters may limit bioturbation and the numbers and kinds of tubes and burrows produced. It may also be desirable that the sediment be free of broken shell and any other gravel-sized particles that may compete with heterogeneity due to bioturbation. Horizontal volume and topographic heterogeneity thus may be quite limited, although seasonally present methane bubbles and ebullition can cause substantial vertical heterogeneity and some burrow-like horizontal heterogeneity produced by ebullition pathways through the sediment.

In the field experiment, the anticipated spatial and temporal scales of environmental processes must be accounted for in the acoustic sampling strategy. Thus, probe arrays should be capable of resolving important small-scale phenomena, and the interval between measurements must be short enough to resolve the most rapid environmental changes of interest. At the other end of the scale range, duration of deployment and areal coverage of the experiment must be sufficient to capture the large-scale variations of interest.

A final field effort, if warranted by demonstrated understanding of the sand and mud end members, would be conducted in a region of much more substantial horizontal and vertical heterogeneity. Availability of historical data would be balanced against ease of measurement in real time with instruments developed and adapted for the program and against ability of the evolving models to deal with multiple scales of heterogeneity. Candidate sites could include environments

ranging from estuary-inlet complexes with lenses of varying bed material produced by channel migration to more gradual and more slowly time-varying gradients seen in estuarine sounds.

8. Conclusions

The problem of acoustic propagation and scattering in coastal sediments is at a stage where a relatively modest investment should yield significant scientific progress. Several hypotheses, in the form of models, await experimental tests, and controlled experiments with improved resolution will foster the development of improved models. If the recommendations of this workshop are properly executed, several advances may be expected.

- Identification and analysis of acoustic propagation and scattering processes, including the effect of porous media, scattering from trapped gas bubbles, biological organisms, bioturbation, and microtopography, with spatial and temporal statistics as far as practicable, and verification of cause-effect relationships.
- Acoustic propagation models to remedy the shortcomings of existing models, particularly in the area of penetration of sound into sediments at shallow grazing angles.
- Acoustic scattering models of improved accuracy.

The resulting acoustic models will be based on a sound understanding of the underlying physical processes and their biological, mechanical and chemical forcing functions. The final results will form the foundations of improved sonar performance models with superior predictive capability compared to existing ones. They also will determine the limits of acoustic measurement (e.g., tomography) of sedimentary properties.

Figure Captions

Fig. 1 Comparison of predictions (Left) and measurement (Right) of sonar beam transmission through a water-sand interface (Williams et al. 1989). The incident grazing angles are 51.9° (Upper) and 25.8° (Lower). The latter angle is equal to the critical angle, for which sound is refracted horizontally. The shading indicates the region in which comparisons of prediction and measurement are considered valid. Comparison of contour lines in this region for the two lower figures suggests that acoustic energy penetrates the bottom at a steeper angle than predicted.

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Coastal Warfare Optics and Electromagnetics
A Workshop on
Research Needs and Opportunities for the Changing World

assembled and edited

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Coastal Warfare Optics and Electromagnetics
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Coastal Warfare Optics and Electromagnetics
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1.0 Introduction

The US NAVY in future conflicts will likely be required to operate in coastal water. Third world submarines and mines are viable threats in shallow water. Acoustics, the historical mainstay of the NAVY, has much less capability here than in the open ocean. Fortunately Optical Technology has advanced in recent years. Present day and future optical systems can usefully complement and supplement the environmentally limited acoustic sensors. However water clarity is still the prime determinate of any through-water optical system's performance.

The problem is that most studies of water clarity have been done in the open ocean. As one approaches the shore proximity of land and benthic bottom adds several significant processes which impact the nature of coastal water and greatly increases its turbidity and variability in space and time over that of open ocean water. The Persian Gulf War demonstrated again that little information exists about coastal water clarity and its spatial and temporal behavior. Such knowledge is vital in Mine Counter Measure (MCM) operations.

Basic research is needed to understand light propagation in the coastal zone the manner effected by the water's optical properties and how these properties depend on and and covary with the coastal ocean's physical, geological, and biological processes. Additionally it is desirable to determine whether the degree that opportunities exist to fruitfully apply research methods and knowledge from optical physics, inverse modeling, and mathematics to better understand and study the optics of the coastal zone.

1.1 A Workshop Identifying Science Needs

Recognizing that a potential science deficiency in the area of coastal water optics exists, the Office of Naval Research and the Naval Research Laboratory, Stennis Space Center, conducted a workshop on 10-11 March 1992 in Arlington VA to assess the present state of science. Workshop participants are identified in Attachment B.

A workshop goal was to suggest the most meaningful areas where ONR could invest in future research. The Workshop agenda is shown

in Attachment A. Experts in the areas of coastal water circulation, sediments, biology, and optical oceanography were brought together to define the processes effecting optical and electromagnetic propagation in the coastal region. They evaluated relevant experimental and theoretical, and modelling knowledge. They discussed the complicated, often non-linear and chaotic interactions of the physical, biological, and geological processes that combined to define local instantaneous water clarity. They noted deficiencies and made suggestions that could be used to efficiently direct future research. Optical physicists, mathematicians, and inverse modelers also participated. Their role was to see if methods used in their respective disciplines might be applicable to the problem of coastal optics and electromagnetics.

1.1.1 Workshop Goals

Explicit workshop goals defined in the invitation to participate were to:

* understand the physical processes and develop models to predict optical and electromagnetic scattering, absorption, and propagation phenomena from the surface to the benthic layer in the coastal zone,

* relate deterministically and (or) stochastically these optical and electromagnetic phenomena to hydrodynamic, physical, biological, and geochemical processes in both the spatial and temporal domains, and

* develop optical diagnostics and associated analysis techniques to identify and quantify these processes.

1.1.2 Workshop Format

The workshop started with an introductory talk by ONR as follows:

Introduction - why ONR and the NAVY are interested
Historical background and future projections
- World War II experiences
- landings - water depth and mines
  - ASW - 95% in shallow regions

Recent
- Kuwait and the Persian Gulf
- Marines landing
- Mini-subs

Future
- Mines
- Amphibious Operations
- Coastal ASW

Goal of work shop:
- To produce a document that lists and prioritizes the science issues needed to understand the coastal zone including a statement of where we are today.

Approach

Mechanistic and Process Oriented Science

How do things work

How are processes coupled - the coast as an open system

Multidisciplinery science - working together

Oceanography - physical, biological, geological, optical coupling, etc.

Physics - optics, technologies, diagnostics, processing

Mathematics - Inverse and forward modeling, etc. efficient and fast methods of solution, etc.

By design the participants were chosen to represent many different scientific disciplines. The first morning, tutorials on the currents, sediments, biology, optics, and acoustics of the coastal region were presented to provide a common education on coastal processes for all involved. Additional tutorials on developments in gated optical physics and the mathematics of inverse modeling were presented to educate the oceanographers to new techniques.

The remainder of the two day time-period was devoted to subcommittee meetings the results of which were presented to the main body for further discussion and refinement. It was important that each group fully understood the issues confronting their area of interest and to be aware of how the other areas were connected through the complex physical and biological processes in the coastal zone. The leaders of the subcommittees then submitted reports to ONR after the meeting adjourned.

The second section of this report is a condensation of those reports editted to show the interrelationship of each process area on the optics of coastal waters.

1.2 Case I or Case II - Optical Classification of Water

A useful classification system due to Andre Morel divides ocean waters into two classes. This classification was used throughout the workshop and is presented here.

Case I water refers to open ocean water far away from land effects where the dominant process defining optical properties is the amount of chlorophyll in the phytoplankton present. Here the optics of Case I waters covary directly with the amount of chlorophyll present. Case II water is that found in the coastal region and in other regions where additional processes such river runoff with mineral and organic particulates and solutions color the water brown or yellow. Although biological processes are still operating they may not be the dominant process and the optical properties will be a complicated function of many independent processes. It is the understanding of these often independent complicated processes that make the study of Case II coastal water

optics more difficult than the open ocean Case I water.

1.3 Overview of Processes Effecting Coastal Optics

The optical properties of coastal waters are determined by the particulates and dissolved material present in the local water column. Some of this material is due to local biological activity and some by geologic processes. Advection carries in material from more distant biological and geologic sources.

The biologic processes are driven by the available light (insolation) from the sun which is a function of time (seasonly, hourly, etc.) and locale. Water clarity greatly effects biological activity as does the availability of nutrients (e.g. N,P,Si, etc.). Nutrients in turn are advected by horizontal and vertical currents which are effected by local topography. Nutrient sources may come from adjacent land carried by rivers, rainfall, etc. and from reservoirs in the sediments from past biological decomposition. Biology is also effected by the local water density structure (vertical and horizontal) which is generally defined by the temperature (sun, optical absorption of the water, wave mixing, etc.) and in the coastal zone by fresh water land runoff.

The geologic processes provide particulates to the water column from land runoff erosion events and from bottom sediments which may be disturbed by biology, surface waves, and water currents.

The currents and surface and internal waves that advect the particles and disturb the sediments are themselves related to near and distant meteorological events (sun, wind, etc.) and surrounding and distant topography.

The net result is that the optics of the coastal region are determined by the interaction of a complicated and probably non-linear combination of physical, geological, and biological processes changing rapidly in space and time. Thus many diverse areas of oceanography must necessarily be involved in studying coastal optics and diagnostic and modeling tools and methods developed in physics and mathematics may be required to solve this difficult problem.

2.0 Reports of the Subcommittees

The reports are ordered logically to exhibit the interacting processes effecting coastal water visibility. Section 2.1 abstracted from the report of Dr. Steven Lentz discusses the alongshore, cross-shelf, and vertical circulation of water, i.e. currents and waves, which moves sediments and other particulates and transports biological nutrients in the coastal region. Section 2.2 abstracted from the report of Dr. Patricia Wiberg then

describes the problems of sediment populations and dynamics as effected by the water circulation. Section 2.3 condensed from the report of Drs. Mary Altalo and Alan Weideman presents the effects of biological productivity in determining the nature of the dissolved and solid biological component of coastal and estuarine water. These three sections introduce the processes which determine the coastal water optical properties by the production and three-dimensional transport of particulates and dissolved substances.

Section 2.4 contributed by a sub committee chaired by Dr. Ronald Zaneveld examines the optical differences between the more thoroughly studied open ocean water(Case I) and the turbid coastal water (Case II). The complicated nature of the increased amounts of suspended and dissolved material in the coastal water appear as problems in the propagation of natural and man-made light fields and in the consequent design and evaluation of systems using light.

After identifying the processes setting the optical properties of coastal water and in turn how these properties effect visibility and light fields, consideration was given to the question of the degree that research methods in optical physics and inverse modeling and mathematics might be usefully applied in studying the coastal optics problem. Section 2.5 is a report by Drs.Reintjes and Duncan of NRL on developments in Optical Physics and Diagnostics which could be applicable. Section 2.6 by Dr.Margaret Cheney examines possible applications from mathematical science and inverse scattering that might be useful.

2.1 Physical Oceanography Summary (Dr.Steve Lentz)

Physical oceanography processes play an important role in the distribution of particles and hence the water clarity over the continental shelf. Such processes can influence both the source of particles and the displacement of particles from their source. Examples of physical processes which influence the source of particles are coastal upwelling where nutrient rich deep water is brought up into the euphotic zone resulting in biological productivity and bottom stress events which resuspend sediment upinto the water column. Shelf lows, both vertical and horizontal,and mixing processes may then displace and redistribute particles in the water column.

The optical oceanography focus is on Case II water (defined previously) and the transition between Case I and Case II waters. Three regions of the continental shelf which are likely to be characterized as Case II water are 1) the bottom boundary layer, 2) the inner shelf, and 3) estuary outflows. The transitions between Case I and Case II waters may be characterized by an abrupt change, i.e. a front. The bottom boundary layer, the inner shelf, estuary outflows, and fronts are all at present poorly understood aspects of coastal physical oceanography. A brief overview of each of

these elements is given below.

2.1.1 The Bottom Boundary Layer

The bottom boundary layer dynamics influence the resuspension and subsequent spatial and temporal distribution of suspended sediment over the continental shelf. The bottom boundary layer provides an important pathway for transport of suspended sediment, particularly cross-shelf transport. At present the bottom boundary layer dynamics over the continental shelf are not well understood. For example, little is known about the spatial scales of the bottom stress which is responsible for sediment resuspension events. Also, the vertical distributions of both the velocity and turbulent kinetic energy (mixing) are poorly understood.

2.1.2 The Inner Shelf

The inner shelf can be crudely defined as the region extending from the wave breaking zone, water a few meters deep, offshore to water depths of a few 10s of meters. This region can vary in width from less than a kilometer on the west coast of the United States to several 10's of kilometers on the east coast. Observations indicate that the inner shelf is usually characterized by relatively large suspended sediment concentrations. Because it is shallow the inner shelf can be an important region for vertical exchange both through mixing and vertical advection and hence provides an important pathway between the lower (bottom boundary layer) and upper(surface boundary layer) water column. While considerable progress has been made in understanding the physics of the nearshore and midshelf regions, the intervening inner shelf has received relatively little attention. Consequently, little is known at present about the inner-shelf dynamics.

2.1.3 Estuary Outflows

Estuary outflows can provide a direct injection of particle laden water onto the continental shelf. These outflows can consist of a single small or large point source such as the Mississippi River discharge, or a more distributed source such as the Gulf of Alaska coastline. Because of the bouyancy force associated with the relatively fresh discharge, estuary outflows can drive significant shelf circulations. In general, estuary outflows represent an important area of shelf dynamics that is poorly understood, due in part to the inherent non-linear nature of the physics. Of particular interest to the optical properties of the water is how and where exchange occurs between the plume water associated with the outflow and the ambient shelf water. This is directly related to understanding estuarine frontal dynamics discussed below.

2.1.4 Fronts

Fronts are regions of strong gradients separating adjacent water masses having different properties. Satellite observations have emphasized that fronts are a ubiquitous feature of the coastal ocean. There are a wide variety of different types of fronts in coastal regions. Examples which may be relevant to transitions in the optical properties of the water include the following. Estuary plume fronts which separate the fresh outflow water from the ambient shelf water. In regions with strong tides, tidal mixing fronts separate a well-mixed shallow region dominated by tidal mixing from a deeper stratified region. Coastal upwelling fronts associated with the offshore advection of surface water. While the presence and importance of fronts has been recognized the physics of these features are poorly understood. At present most traditional observational techniques are not well suited for studying frontal features. This is due in part to the mix of disparate scales, short cross-front scales and large along-front scales and because of the transient (temporally and spatially) nature of fronts.

Two particularly important questions are what maintains particular fronts, and how and to what extent cross-frontal exchange occurs?

2.1.5 Summary

Coastal physical oceanography processes will play an important role in determining the spatial and temporal distribution of Class II water on the continental shelf. Many of the shelf regions and processes likely to be associated with Class II water are presently not well understood. Thus a better understanding of Class II water will require a better understanding of the physical oceanography.

2.2 Coastal Sediment Dynamics (Dr.Patricia Wiberg)

Progress in our understanding of coastal sediment dynamics requires an approach that integrates theoretical work on the basic mechanics of sediment motion in wave-dominated environments, measurements of sediment in the bed and in the water column, and instrumentation to make the necessary measurements. The desired end product of this work is a basic understanding of sediment dynamics and, more tangibly, broadly applicable predictive models. It is my opinion that in our present state of understanding, model development has outpaced our ability to measure sediment distribution in the water column to the accuracy necessary to validate the models. There are, however, many other important problems remaining to be solved related to the distribution of sediment in the water column involving basic sediment mechanics, physical oceanography, and biological oceanography. These topics

are briefly discussed below.

2.2.1 Instrumentation and Necessary Observables

Testing our understanding and models of the distribution of sediment in suspension requires at a minimum measurements of particle concentration and particle size distribution as a function of distance from the bed. A number of instruments are currently available to measure concentration including transmissometers, nephelometers, Optical Backscatterance Sensors (OBS), acoustic backscatter profilers, lasers, plankton cameras, and, of course, direct physical sampling. Some of these are commercially available and widely used, others are in prototype.

Each has limitations (see Table 1 which gives an summary of the state-of-the-art of instrumentation) but in general the problems with the indirect measurements (all but physical sampling) is that the calibrations needed to convert the measured signal to sediment concentration tend to be dependent on grain size, the instruments are generally not effective through the entire range from very low to very high concentrations, and many of them are rather intrusive. In addition to concentration, grain size information is needed to obtain accurate particle concentrations from indirect measurements and to test our understanding of sediment mechanics. Models of suspended sediment distributions indicate progressive fining of suspended load away from the bed, and a suspended load that is typically significantly finer than the grain size distribution of the bed. However measurements of size distributions of suspended load are lacking.

Another important parameter in suspended sediment calculations is settling velocity, which is a function of particle size and density. For noncohesive sediment, settling velocity is fairly well known, but this is not the case for aggregated particles. Aggregates are relatively large but have a low density and are very fragile and cannot be transferred to a laboratory for settling rate measurements. Several instruments in prototype stage are designed to directly measure settling velocity. When combined with measurements of particle size, particle density can be inferred. Density and size information together may allow different types of particulate material to be distinguished, e.g. single quartz grains, aggregate particles, organic particles.

Settling rate also depends on particle shape and angularity, factors that may also be important in chemical reactivity and benthic biological processes. Suspended sediment distributions are also dependent on bed properties, especially its grain size (and density) distribution and surface roughness. Most of what we know currently has been determined from cores and photographs. Some indirect measure of surficial sediment properties (i.e. of the upper 10cm or so) that could be related to grain size would be very valuable in assessing the heterogeneity of surficial sediments and

TABLE 1: Suspended Sediment Measurement Instrumentation
(courtesy of C.R. Sherwood, Battelle NW)

Transmissometers:

Pros: Effective at low concentrations, measure light transmission directly, fairly inexpensive.

Cons: Instruments are large and intrusive, relatively high power requirements, limited dynamic range, ineffective at high concentrations, concentration calibrations are size-dependent and non-linear, prone to fouling.

Optical Backscattering Sensors (OBS):

Pros: Small, durable, relatively unintrusive, relatively low power, fairly wide dynamic range, linear calibration, inexpensive.

Cons: Calibrations are size-dependent, nothing useful is measured directly, prone to fouling.

FOBS: (fiber-optic OBS)

Pros: Even smaller and less intrusive than OBS, lower power requirements, all other advantages.

Cons: Still in prototype stages, calibrations may not be linear, same disadvantages of OBS.

Acoustic backscatter sensors:

Pros: Non-intrusive, long-range measurements, profiling capability, fairly large dynamic range, resistant to fouling, use of multiple frequencies allows some size estimation, provide direct measurements of acoustic scattering.

Cons: Difficult to calibrate (big tanks required), large power requirements, calibrations are size-dependent, removal of sonar equation effects (attenuation with distance) is non-linear because of particle scattering, so derivation of concentration profiles is tricky and not (yet) convincingly demonstrated. Expensive, mostly prototypes.

Lasers:

Pros: Non-intrusive, all the advantages of good transmissometers, can (in theory) provide size distribution statistics and particle velocities at same time.

Cons: Relatively low dynamic range, only for low concentrations, size-dependent calibration in transmissometer mode, inversion of sediment sizes not convincingly demonstrated yet, expensive, power intensive, all field devices are prototypes, lab devices are commercially available but still require calibration verification.

Physical samples:

Pros: Only way to get mass concentration, proper sampling can preserve particle size/shape, but very difficult, no limits on dynamic range and no calibration problems.

Cons: Intrusive, difficult to sample without disturbing particles, expensive to obtain lots of samples, especially closely spaced in time/space.

Plankton Camera:

Pros: Rich detail on size, shape, volume concentration.

Cons: Very large and intrusive, data very expensive and time consuming to process, good only for fairly low concentrations.

constrain sediment type. Similarly, it may be possible to relate indirect, integral measures of surface roughness to the roughness parameter needed in boundary layer flow calculations -- such a measure might be particularly useful over biogenic roughness. Measurements of this type using a sonar device have been attempted, but a fine sediment bed is not a very good reflector because of the high water content.

As a final note, it is worth mentioning that some of the measurements/ experiments needed to resolve the important questions in sediment dynamics must be made in the field, but some are more appropriately made in a controlled laboratory setting. For these problems, new technology that is not yet ready to withstand the rigors of operating in the ocean may be able to be utilized in a flume or wave tank.

2.2.2 Theory and models

In many respects, boundary layer flow and sediment transport theory and models are ahead of our ability to measure the parameters necessary to test them. Boundary layer flow measurements do support the basic formulation of wave-current interaction models, and recent measurements on the northern California continental shelf (in ONR's STRESS program) have provided the first comprehensive set of suspended sediment concentration data to test the suspended sediment calculations in the boundary layer models. These measurements include OBS, acoustic backscattering, transmissometer, and physical measurements of sediment concentration in the water column.

One important problem that remains unsolved is the proper characterization of the near-bed suspended sediment concentration, which serves as the boundary condition for computing suspended sediment profiles. Without this parameter, we can predict the distribution of sediment in the water column, but not the total volume. Attempts to infer this parameter from boundary layer measurements have met with limited success because of the complexity of the environment and the inability to directly measure low and sediment concentration in the wave boundary layer (as well as the problems with instrument calibration and range mentioned in the first section). This is a measurement that still remains to be adequately made in a flume, and would be a good candidate for testing the ultimate potential of a new instrument for measuring suspended particulate material.

There are other aspects of boundary layer flow and sediment transport processes that are less well understood and require further theoretical and modeling work. High on this list is the effect of bed surface processes on controlling the volume of sediment in suspension and its distribution. For example, small-scale bedforms are almost always present on sandy beds,

except perhaps at very high flow conditions. Flow over these sharp-crested, wave-generated bedforms is spatially complex, with an internal boundary layer just above the bed surface and an overlying wake region. It is the stress at the bed surface that mobilizes sediment, and sediment going into suspension must move through the zone of wake-dominated turbulence before entering the flow above the bedforms. As far as I know, the effect of bedform momentum reduction, spatially varying stress, and wake turbulence on the transfer of sediment from the bed into suspension has not been investigated.

Bedforms also affect the hydrodynamic roughness of the bed, and bedform migration rate is related to bedload transport rates and bed armoring. Crude parameterizations of bedform roughness have been made, but this problem will require more work, as will determining the drag coefficient of these bedforms, a related parameter needed to calculate average shear stress at the bed and bedload transport rates. It has also become clear in modeling work on suspended sediment concentrations that bed armoring, including coarsening of the bed surface as fine sediment is winnowed out, may exert a large control on the volume of sediment suspended in the water column. This problem needs to receive more attention, both theoretically and experimentally. As mentioned below, benthic organisms may also play a significant role in bed roughness and sediment availability.

2.2.3 Physical Oceanography and Sediments

There are many important flow problems that relate to sediment distribution in the water column. Here I mention just two that have significant implications on sediment transport and represent areas of uncertainty in our current models.

In theory, sediment can be suspended to the height of the bottom boundary layer. Medium to coarse sediment would never reach this height, but very fine sediment can and does. As a result, the volume of fine sediment in suspension depends in part on the height of the bottom boundary layer, which varies seasonally and during storm events. A better understanding of the controls and variations in boundary layer depth are needed.

A second question, also related to the bottom boundary layer, is an understanding of cross-shelf flow and advection of particulate material in suspension.

2.2.4 Sediments and Biological processes

Biological processes at the sediment/water interface may control roughness and elastic/strength (stress/strain) relationships within the upper few millimeters and/or centimeters of fine-grained sediments (silts and clays) such as are often found at mid-shelf depths. Their impact should be modeled or included in

erosion/deposition or sediment transport models. The type/size structure of fine particles available for suspension in coastal environments are probably controlled by benthic biological processes, including bioturbation, geochemical/biochemical processes, and algal and bacterial binding.

2.3 Biological Issues in the Coastal Zone (Drs. Alan Weidemann and Mary Altalo)

The Biological subcommittee summarized their report in terms of three issues. The first issue concerned the space and time scales of biological communities i.e. the size and growth rates of plankton blooms, etc. The second concerned the feedback interactions of the environment (e.g. light level) on individual organism physiology (e.g. a phytoplanter's chloroplast development) and the resulting change in the environment (e.g. light gets greener) as the organism changes (e.g. more chlorophyll absorbs blue light). The third issue considered the interaction of the biology with the benthos, the manner in which organisms would perturb the bottom sediments, e.g. how this might effect the light field, and how this in turn would effect the biology.

2.3.1 Time and space scales of biological succession in coastal environments

The following are Research questions:

1. What is the controlling factor that mediates the sunkton groups in coastal environments and how does the physical forcing of the coastal environment influence these controlling factors?

2. To what degree do resuspended particulates mediate population dynamics in a coastal environment? Through which mechanisms si this mediation done, e.g. light level, trace metal or nutrient availability, etc.? Can models of divergence in these controlling factors be used to forecast predictive changes in the vertical and horizontal structure of biological material?

3. What is the temporal cycle for population fluctuations in coastal environments and what controls the onset and crash of phytoplankton blooms? How important are episodic events (1-2 day duration) in modifying biological biomass, and what is the role of perturbation in the succession of the biomass? Can this be modeled employing terrestial perturbation theory?.

4. To what extent are microscale mediated processes that take place at the cellular level translated into larger scale property variability such as in the inherent and aparent optical properties? What measurement techniques can be used

to identify these interactions in scales and what nepheloid layering occurs in the near-coastal zone?

2.3.2 Feedback between Organisms and the Environment

The following are the Research questions in this area:

1. How rapidly do populations respond to changes in the concentration of growth limiting nutrients or to rapid fluctuations in the light field due to a greater physical forcing and changing light fields? With a rapidly mixed environment, what role does photoadaptation and pigment packaging play in changing the quantity and quality of the light field. Are there spectral differences in the absorption spectra at the fine-scale that cascade to the bulk optical properties? How important is fluorescence in observations of coastal water upwelling and the estimation of optical properties from remotely sensed reflectance. Over what time scale does the fluorescence yield change relative to changes in incident radiation and the spectral make-up of the light field?

2. How does biological activity mediate the particle size distribution and volume scattering function in coastal environments? Is the general increase in virus and bacteria concentrations found in coastal environments significant to the overall propagation of light?

3. In Case II waters gelbstoffe contribution to absorption is frequently large. To what extent do biological processes mediate dissolved yellow substance concentration in coastal areas through in-situ production of detrital material? Is there indirect mediation through biological activity on resuspended material or terrigenous sources? What is the role in bio-physical forces in driving gelbstoffe production?

2.3.3 The benthic environment and biological interaction

The following are the Research questions in this area:

1. How does biological activity in the water column translate to benthic particle composition?

2. What modifications in the benthic interface can be ascribed to biological activity? How does production and biological activity in the coastal region influence the elastisity of the benthos or change the physical force necessary before resuspension occurs.

3. To what degree does a nepheloid layer of high production

occur at the benthic-water interface and how does this layer contribute to light and EM attenuation? Are models of particle dynamics capable of including aggregation and bioturbation effects that occur at the benthic-ocean interface? If so, what parameter best measures the change in resistance and conductivity brought about by the biological activity?

2.4 Research in Coastal Ocean Optics (Dr. Ronald Zaneveld)

This report is devoted to listing the research areas previously addressed (but not necessarily solved) in open ocean (Case I) waters. We define the general problems of optical oceanography in Case II (turbid coastal waters). The optics in coastal Case II waters are distinct from open ocean waters (Case I waters) in that the inherent optical properties (IOP)are not simply related to phytoplankton concentrations. A research program should focus on Case II waters and their transition to Case I waters.

The distinguishing element in Case II waters is a significant contribution to the IOP by terrigenous particles and dissolved organic matter.

The Subcommittee on Coastal Optics has defined the following as the central scientific issues to develop the science of Coastal Optics. These issue areas are:

1) Radiative Transfer in Case II waters.

2) Relationships between the inherent optical properties and the properties of dissolved and suspended materials.

3) Distribution of IOP in 4-dimensions (x, y, z and t) as related to physical, biological, chemical and geological oceanography.

4) Development of optical instrumentation and measurement techniques for Case II waters.

The significant questions concerning each of these major research issues in optical oceanography for Case II waters are discussed in the following sections.

2.4.1 Radiative Transfer

1. Can the IOP and AOP be measured and can closure be achieved?
2. Can the space and time scales of the IOP and AOP be resolved sufficiently well to solve the 4-dimensional equation of radiative transfer?

3. What are the relevant time and space scales of the distribution of the IOP and AOP in Case II waters.

4. How do radiative transfer models change in situations where the interstitial particle spacing is very small (i.e. 2 to 3 particle diameters).

5. Can passive remote sensing be used to estimate the IOP in Case II water masses.

6. Can LIDAR systems be used to infer the vertical and horizontal structure of the IOP in Case II waters (for example, can LIDAR be used in Arctic regions)?

7. What is the influence of the bottom boundary on radiative transfer? (In many situations the bottom boundary layer may be Case II., while the waters above it are Case I)

8. What is the influence of the air-sea interface on radiative transfer models and underwater light fields?

9. Can the radiance field be inverted in a multiple scattering regime to obtain the inherent optical properties (i.e. to what accuracy is time and space can the IOP be resolved)?

2.4.2 Relationship of IOP's and Dissolved and Suspended Materials

1. How do the size, shape and index of refraction distributions of the suspended particles (including bubbles) affect the spectral absorption coefficient and spectral volume scattering function?

2. What is the relationship between the yellow matter and it's specific spectral absorption coefficient?

3. Is there a method for inverting optical measurements to obtain the concentration and nature of suspended and dissolved materials.

2.4.3 Vertical, Horizontal, and Temporal Variability

1. What are the source, sinks and processes governing evolution of yellow matter and particles in Case II and transition waters?

2. On what space and time scale must the IOP be resolved precisely (i.e. organized structure), and/or to what extend can they be described statistically, to obtain meaningful radiative transfer results?

3. What are the processes that govern the transition of the optical properties from Case I to Case II waters?

4. What processes influence the distribution of the IOP at a specific site?

5. How does one describe the processes at a specific site in order to provide predictive capability of the optical properties? Is a set of measurement protocols necessary?)

6. What is the effect of the physical forcing of water mass structure, and its associated biogeochemistry, on the distribution of the IOP?

7. How do the surface roughness and vertical structure of the IOP influence the remotely sensed radiance? Can the remotely sensed radiance (for example, from SeaWiFS be inverted to obtain distributions of the IOP.

8. What is the importance of fluorescence and other transspectral scattering sources?

2.4.4 Instrument and Technique Development

1. As indicated in the issues mentioned above, new instruments must be developed to measure spectral absorption, attenuation and volume scattering functions in Case II waters. This requirement is driven by considerations of dynamic range, spectral and temporal scales of variability, and small optical measurement scales. These instruments should be developed for profiling, moored, towed and drifting modes.

2.Measurement techniques must be developed that take account of the special conditions that may prevail in Case II and transition waters. These conditions may include surface and bottom boundaries, as well as very small space and time scales, compared to typical instrument dimensions. (We currently have no instrument to characterize bottom spectral reflectance and its heterogeneity.)

3. New LASER based instruments should be developed to determine IOP non-intrusively and in real time (e.g. on ROV's).

2.5 Optical Physics and Diagnostics as Applied to the Coastal Optics Problem (Drs. Michael Duncan and John Reintjes)

Optical diagnostics, in general, can provide a wide variety of information on fundamental properties of coastal water. Of primary

interest here is identifying measurements that can provide information that is needed by the various groups working on understanding the physical properties of case II water. That information includes inherent and apparent optical properties needed by ocean optics groups, particulate information (suspended particle size, concentration, distribution, and composition) needed by ocean dynamics and sediment groups, and propagation, scattering and reflection information needed by mathematical modeling groups to formulate and verify mathematical models. It should be stressed that optical diagnostics play a particularly important role in mathematical modeling since experimental measurements of the real optical properties of water and its constiuents are used both to provide input intc the models and to check the predictions generated by the mouels.

The important quantities that need to be measured for the above models are the size, distribution, and nature of the suspended particles in case II waters. For comparison with model predictions, beam extinction coefficients and forward and backward scattering coefficients need to be determined. In the course of these measurements it is vital to take into account the inhomogenity of the coastal zone water. Laboratory measurements on samples are valuable in identifying the suitability of techniques, for evaluating specific samples, and for verifying codes. Ultimately, however, in situ measurements over the full extent of conditions will be needed.

Current optical diagnostic techniques involve passive remote sensing and active sensing. Passive probing is suitable for depths on the order of one extinction length. Active probing can provide measurements on beam extinction and scattering parameters, but current techniques are limited to a few extinction lengths due to the turbidity present in coastal waters. Measurements from the sea surface to the ocean bottom are essential due to the diverse conditions present in various layers of the water column.

Several new optical techniques may be able to provide much needed additional data for case II waters. Time gated measurements can be used to measure to 30 extinction depths, providing information from the sea surface to the bottom in most of the coastal regime. Time gated measurements giving a complete time history of a reflected or transmitted short pulse when combined with angular scattering data can be used to provide direct information on forward extinction coefficients, particle distributions throughout the water column, and radiative transport in both the single scattering and multiple scattering regimes.
Time gated imaging of internal layers of the water can provide direct measurements of the size and distribution of scattering centers. Measurements at different wavelengths can be used to identify biological and specific mineral components. Doppler heterodyne or homodyne measurements may be able to provide information on inner zone upwelling.

These optical measurements must be done over a variety of scale sizes in order to obtain the information that is critical for the various processes being modeled. For example, centimeter scales may be needed for certain biological processes and for studies of boundary layers, while scales of 10's or 100's of meters may be needed for sediment transport studies. Active optical measurements can be used to obtain point measurements at various grid spacings and are appropriate for use at the smallest resolutions needed. Time-gated imaging techniques can be used over much larger areas and are typically only limited by available laser power.

References (and references contained therein) on time-gated techniques

M. D. Duncan, R. Mahon, L. L. Tankersley, J. Reintjes, "Imaging through a low light level Raman amplifier," in Nonlinear Optics, Vol. 1409, SPIE, Bellingham, Washington (1991).

M. D. Duncan, R. Mahon, L. L. Tankersley, J. Reintjes,"Time Gated Imaging through Scattering Media Using Stimulated Raman Amplification Opt. Lett., 16, 23, p. 1868 (1991).

M. D. Duncan, R. Mahon, L. L. Tankersley, J. Reintjes, "Quantum limited imaging in a stimulated Raman amplifier and applications in time-gated imaging through scattering media," *to be published in* Nonlinear Optics, Vol. 1626, SPIE, Bellingham, Washington (1992).

2.6 Mathematics and Inverse Modeling and Coastal Optics (Dr. Margaret Cheney)

The overall goal is to develop mathematical techniques for extracting information about the water and bottom from electromagnetic data.

2.6.1 Inverse Problems

The solution of an inverse problem obtains information about an inaccessible region of space from measurements made in an accessible region. A concern is the information content that might be extracted. What medium parameters can theoretically be extracted from what kinds of data? Three issues are of importance in considering the inverse approach to coastal optics studies.

1. SOURCE DESIGN. If an active system is being used, we have control over the spatial and temporal variations of the probing signal. The optimal space-time shape of the probing signal needs to be determined.

2. DATA MEASUREMENT. We need to formulate and study the inverse problems associated with data that is limited in spatial and temporal extent and in accuracy.

3. *PROBLEM GEOMETRY. Theory for inverse problems involving* half-space geometry needs to be developed.

2.6.2 Stochastic Approaches to Inverse Problem

2.6.2.1 Stochastic Modelling

In many problems the statistical characteristics are more important than the actual configuration of the medium. This requires modelling wave propagation through the medium by a stochastic partial differential equation and modelling the boundary conditions at the ocean bottom and at the sea-air interface as random fields (two-dimensional random processes). Little is known about inverse problems for stochastic partial differential equations.

2.6.2.2 Combination Problems

It may be possible to formulate the ocean optics inverse problem as a combination of a problem of reconstructing one or more functions and a classification problem, which involves a choice of one of several known possibilities. For example, suspensions and bubbles lead to additional scattering, but the characteristics of scattering from each is roughly known.

2.6.2.3 Time-dependent Inverse Problems

Inverse problems in which the medium varies with time deserve more attention.

2.6.2.4 Issues for each Inverse Problem

For each of the above problems, he following issues need to be studied.

1. UNIQUENESS. Do the data uniquely determine the medium?

2. POSEDNESS. Do small perturbations in the data correspond to large changes in the medium?

3. ADMISSIBILITY OF DATA. Do given data correspond to an actual medium, or has the data been so corrupted by measurement error that there is no medium corresponding to the data? Knowing the class of admissible data might make it possible to correct for measurement errors.

4. FAST ALGORITHMS. Develop fast and stable algorithms for obtaining medium parameters from experimental data.

2.6.3 Image Intepretation and Analysis

Once an appropriate mathematical model has been formulated, the question of target identification can be considered. Assuming that the target shape is known to within some random variation, e.g. position, orientation, and overall size, can one develop methods, based upon the observed image or images, for locating the target? Often there are degrees of freedom for the target other than location, scale and orientation. Can one develop more general target shape models? Similarly, an important consideration for potential applications is when the target is partially randomly occluded (e.g. by sand). One would like the methods to handle this in a natural way. We wish to develop stochastic geometric modeling techniques appropriate for these problems. For multispectral data or in the case of several different sensor technologies being used simultaneously, the question of compatibility arises; how should the resulting data be used? In the case of target identification, target-dependent noise needs to be considered. This is an added difficulty on top of independent, additive measurement noise.

2.6.4 Stochastic and Deterministic Modelling of the Medium

Issues in this area include:

1. THEORY OF SUSPENSIONS. The current work being done to

understand he dynamics of particles suspended in a fluid should be continued. A related problem is to predict the effects of suspended particles, organisms, and bubbles on propagation of electromagnetic waves.

2. STOCHASTIC MODELLING. Can our knowledge of deterministic modelling be exploited to improve stochastic modelling? Probabilistic models can be used to replace a complicated medium locally by an equivalent homogeneous one for which the inverse problem is much simpler. How accurate are these effective medium theories? How sensitive is wave propagation to variations in the medium parameters? What other stochastic theories can provide useful models?

3.0 Suggestions of the Coastal Optics Workshop

Modeling, Laboratory, and Field Research should address the following Coastal Optics and Coastal Environment issues:

1. PROCESSES It will be necessary to define, measure, and model the processes effecting Coastal water clarity. It will be necessary to consider currents, waves, sediment sources and sediment flow, and the classification and tracking of coastal and terran biological products. Other process issues include production, advection, insolation, predation, meteorological forcing, e.g. wind, and light absorption and scattering.

2. SPACE AND TIME SCALES The spatial and temporal scales of the processes that contribute the particulate and dissolved material to the coastal ocean must be determined together with the way that the various processes spatially and temporally interact. How do we get synoptic data in a highly variable regime? What are the minimum time/space scales needed?

3. UNIQUE COASTAL WATER OPTICAL PROPERTIES The optics of the coastal region may often differ greatly from the optics of open ocean water. Near shore most of the particulates (e.g. eroded sediments) determining the light scattering and absorption originate on the adjacent land. This imparts a uniquely different optical properties than found in open ocean water far from land. Additionally dissolved yellow material from terran plant decomposition products color the water yellow and brown and cause the optics of the coastal waters to differ profoundly from the simpler open ocean water away from land. These processes and their effect on coastal water must be studied.

4. VALIDITY OF APPARENT VS.INHERENT OPTICAL PROPERTY CLOSURE

Because coastal water often is quite turbid, multiple scattering greatly exceeds that seen in the open ocean. Thus techniques relating Apparent (AOP) to Inherent (IOP) Optical Properties routinely used in the open ocean must be reexamined at a fundamental level and perhaps modified or reinvented before they can be used in the coastal environment. A second part of this is that the predictive capability of the standard Radiative Transfer Models must be reexamined and tested in this extremely scattering environment.

5. OPTICS LINKED TO METEOROLOGY, PHYSICAL OCEANOGRAPHY, AND SEDIMENT DYNAMICS Forward Model development and verification is necessary linking the meteorology, the coastal currents and waves, the riverine and estuarine flow, the sediment transport, and the various processes producing biological and geological particulates and dissolved material with the water optics and the resulting propagation of light. How do we decide which processes to model, e.g. those controlling radiative transfer, and/or those controlling biological dynamics? Which models do we build, e.g. deterministic and/or stochastic? Desirable models will be those whose performance can be quatified within prescribed limits. What approximations can we build in, e.g. the weather? what sampling strategies can be used?

6. INVERSE TECHNIQUES Given the development of forward models and the availability of a large and complete set of remotely sensed data, inverse techniques must be investigated to understand and predictively model Coastal Water clarity.

7. ROBUSTNESS To verify both the forward and backward models we need to define necessary experiments, data collection quality and quantity, and how the data will be assimilated.

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SUMMARY OF MAGNETICS IN COASTAL REGIONS
BY ED MOZLEY

I. INTRODUCTION

The magnetic (electromagnetic) research in coastal regions has been neglected in the past due to combination of minimal research support and the complex nature of the environment. This complexity is in two forms. First, due to the complicated nature of the oceanographic and meteorological dynamics along continental margins, it is very difficult and expensive to acquire the appropriate data at a sufficient density to define the temporally varying electrical properties. In addition, the geological evolution of some margins has been extremely complex over a wide range of spatial and temporal scales. This evolution has resulted in heterogeneous electrical conductivity distributions, which cover dimensions that range from the benthic boundary layer to the upper mantle. An accurate inversion of data acquired over these complex distributions requires dense, high quality data and are very difficult to implement.

Recently, there has been a renewed interest in coastal regions. In November 1989, a workshop on the Geomagnetic and Geoelectric Environment of the Continental Margins that was sponsored by the Office of Naval Research was held in Arlington, VA. A large number of scientists from government, academic and industrial sectors discussed the basic research issues and the results were published (Chave et al., 1990). Large scale phenomena were stressed during this meeting and relationship of this research to Anti-Submarine Warfare was clearly stated. However, out of the four working groups established during the workshop, one group was devoted to small scale electrical structure. The issues and approaches considered by this group are summarized in pages 35-37 (Appendix G) of the workshop report (Chave et al., 1989). The results of this section are germane to the goals of the Coastal Benthic Boundary Layer Special Research Project (SRP).

During the Coastal Benthic Boundary Layer SRP workshops, electromagnetic research issues were discussed in a very limited manner. All aspects of this summary reflect the views of the author and should not be considered as comprehensive or as a consensus of the geomagnetic community.

The research issues that are appropriate for the SRP have been introduced in the following section and are related to specific coastal processes. The next section outlines four basic elements of an approach designed to identify the relationships between remote measurements and the fundamental properties of the sediment. These may then be used to transform indirect observations into a broader understanding

of the complex juxtaposition of processes that take place in the coastal environment. Section IV provides three candidate approaches for mapping microscopic properties onto a representative composite that would contain all the essential information about the sedimentary material. The next section summarizes the approximations that are required to first invert the measurements and those that are associated with the use of this information to develop realistic prediction models. Finally, Section VI provides a few comments on the model verification issue.

II. CRITICAL PROCESSES THAT ARE ASSOCIATED WITH THE COASTAL ENVIRONMENT AND WHICH IMPACT ELECTROMAGNETIC MEASUREMENTS

There are several coastal processes that have a significant impact on electromagnetic measurements. The first would be associated with the complex hydrodynamic characteristics that are common in shallow water. These rapidly changing fluid dynamic conditions can result in large spatial and temporal changes in sediment transport and associated deposition rates. In addition, fresh and salt water exchange through river systems, semi-isolated tidal zones or estuaries can create a high degree of variability in both water salinity and temperature. Within the sediments underling these areas, multiphase interstitial components and significant clay mineral fractions may result in frequency dependent conductivities that are characterized by rapid spatial variations. Finally, the benthic boundary has the added complexity that is introduced by the large amount of biological activity, which can have a significant impact on the pore structure and mineral composition of the sediment. All of the above phenomena leave an imprint on the macroscopic electrical properties that are measured by electromagnetic systems.

II.1 Spatial and Temporal Characteristics of Coastal Depositional and/or Erosional Processes

In complex depositional and erosional settings, the relationship between scales of variability in physical properties over both the vertical and horizontal dimensions must be identified before macroscopic models can be developed. In coastal sediments, the relative magnitude of horizontal and vertical scales may be quite large. These types of sediments result in anisotropic and inhomogeneous macroscopic electrical conductivity distributions that introduce a great deal of complexity into the interpretation of the resulting electromagnetic responses.

II.2 Spatial and Temporal Variability in Salinity and Temperature of Sea Water Within Coastal and Estuarine Settings

The highest conductivity in a coastal environment is provided

by the sea water. Consequently, any variability such as fresh water lensing into the sea water or salt water incursion into estuaries results in significant changes in the distribution of electrical conductivity. Since electrical conductivity depends on temperature as well as salinity, any heating or cooling of entrapped shallow water can directly affect the conductivity. In addition, conductivities can be impacted indirectly though evaporation that will cause an increase the salinity. In shallow water, bathymetric variations result in complex hydrodynamic conditions that induce mixing and enhance interchange with fresh water. These conditions, which are coupled with a long period tidal forcing function, result in a high degree of variability in both temperature and salinity.

II.3 Interaction Between Fresh and Salt Water Phases of Interstitial Fluids

The critical issues that have a major impact on the electromagnetic (EM) response to coastal sediments are as follows: electrical conductivity of interstitial fluids; the relative distribution of fluids from both terrestrial and marine sources; and the relative fractions and temporal variability of freshwater, salt water and gas within the pore structure. In addition to distribution of the various phases of the interstitial fluids, both the microscopic pore structure and the matrix composition have an influence on the bulk or macroscopic conductivity estimates. The pore structure characteristics that are represented as effective porosity, permeability and tortuosity are combined with the fluid conductivities to obtain bulk conductivity estimates. These factors primarily control the ionic conduction through the media and hence are mainly responsible for the bulk values measured.

II.4 Wide Variety Biological Activity in the Coastal Zone Sediments

Most coastal settings foster the development of an extremely wide variety of both flora and fauna in the benthic boundary zone. These biological entities disrupt the depositional fabric of the sediment on both microscopic and macroscopic scales and they influence the deposition and migration of surface material. In addition, they affect the geochemistry in the soils that can result in the formation of various minerals. All of these phenomena have a measurable impact on the resulting matrix material and gross pore morphology that defines bulk conductivity of the sediment.

II.5 Deposition and Mobilization of metallic and clay Minerals

Matrix constitutes are of prime importance to not only mechanical characteristics and acoustic attenuation, but they may also impact frequency dependance of electrical conductivity. Clay content effects the magnitude and phase of

the electromagnetic response due to two basic phenomena that are prevalent in rapid depositional environments. The first is associated with the presence of any metallic conductor immersed in an ionically conducting media. The resulting interface potentials established by the change from electrolytic to electronic conduction results in a frequency dependent conductivity. This may be a factor in marine sediments where placers have been deposited or where metal sulfide deposition has been induced by biological activity. The second phenomenon, which may be the most prevalent cause of a frequency dependent conductivity, is due to the specific cation exchange capacity of many materials found in the benthic boundary layer. These materials (especially clay minerals) generate a membrane polarization within the pore structure that maintain captive cationic clouds. The dense cationic concentrations impede the flow or movement of anions through the sediment matrix and result in frequency dependent conductivity. In addition, the possible existence of non-linear effects in the vicinity of the source or current electrodes should be investigated. The magnitude of the effect and the range of currents that are required to initiate a non-linear response should be well defined before in situ measurements are interpreted.

III. APPROACH TO IDENTIFY THOSE CRITICAL PARAMETERS NEEDED TO DESCRIBE DOMINANT SHALLOW WATER PROCESSES

The approach requires at least four phases. The first uses remote geophysical measurements to identify regions that are characterized by similar physical properties. Next use a suite of in situ measures and core samples to identify specific properties and quantify their variability within each of these regions. Co-located acoustic and electrical measurements can then be used to constrain the data inversion and provide additional information on property distributions. Finally, an appropriate model must be developed using the in situ information to map the small scale properties into averaged geophysical measures. This phase of the work would be implemented in an iterative fashion. Preliminary models would be developed over a suite of sediment types. The model performance will be evaluated with additional measurements acquired over different areas and then the model will be refined to reflect the additional information.

III.1 Measurement Schemes Capable of Rapidly Mapping Variations in Water Conductivity, Water Depth and Sediment Conductivity

The geophysical techniques that are used must be capable of mapping properties in a survey mode with towed instrumentation deployed either in the air, on the water's surface or within the water column. The dynamic measurements are necessary to achieve large areal coverage with minimal aliasing to identify the spatial distribution of the macroscopic conductivity. The

various techniques that are utilized must have a well defined footprint or averaging kernel so that both the spectral (or temporal) and the spatial system responses maybe deconvolved or removed from the data. In the general three- dimensional case, this may not be practical; however, a qualitative estimate of the spatial smoothing of the parameters is necessary to compare results from various techniques. As part of the inverse solution, an estimate of the variance for each model parameter is necessary to define the effective resolution provided by each measurement technique. These mapping tools, when deployed in a reconnaissance role, provide information on the following two fundamental issues: definition of the upper limit on spatial variability and the quantification of the bounds over which the conductivity varies. Candidate systems would include the following: direct current resistivity (Corwin, 1985; Schlumberger and Leonardon, 1934), various types of underwater EM transmitter/receiver configurations (Cheesman et al. 1991), and airborne EM systems using various source-receiver coil combinations (Fitterman, 1990). In addition, each EM system may be operated in a transient or continuous wave mode with each providing trade-offs in hardware capabilities and interpretation advantages.

III.2 Quantify the Variability of the Parameter Values Within "Apparently Homogeneous" Zones as Defined by the Non-invasive Geophysical Systems That Map Only Average Conductivities

In situ probes, core samples and small scale seafloor measurements of electrical conductivity (Bennett et al., 1983) and induced polarization (Vinegar and Waxman, 1984), which are supported by samples of interstitial fluids, should be acquired within a suite of "apparently homogeneous" zones as defined by regional geophysical surveys. These small scale (with dimensions on the order of centimeters) macroscopic conductivity measures of electrical conductivity would be combined with an electron microscopic view of the sediment to provide the necessary information for the development of a viable first order aggregate network or statistical model. In addition, electrochemical and chemical analysis of matrix materials would aid in developing appropriate relaxation models that satisfy macroscopic polarization measurements. This comparison between small scale variability, microscopic physical and chemical properties, and large scale zones (on the order of meters to tens of meters) provides the information necessary to build reliable prediction models that are appropriate for use with remote sensing systems. The in situ measurements have the advantage of being configured as either vertical or horizontal arrays that are positioned either on or within the sedimentary unit under investigation. In addition the probes may include a combination of several vertical and/or horizontal array elements that would provide an imaging capability.

III.3 Acquire Sub-bottom Acoustic Data Co-located With Electrical Property Measures and Use as Mutual Constraints in the Interpretation Phase

Several acoustic sediment classification schemes have been developed over the past decade. These schemes tend to work well to predict or interpolate property variations in the vicinity of borehole (core) with known properties. However, when little ground truth is available these schemes are less reliable and are non-functional in the presence of gassy material. The use of both acoustic and electromagnetic measurements to provide a more robust scheme for the inference of material properties is a reasonable objective since there exist theoretical links between the electrical formation factor and acoustic velocities in ideal fluids (Brown, 1980; Johnson and Sen, 1981).

III.4 Iterative Development of Models that Use Geophysical Measurements to Define Representative Volumes of Microscopic Material Properties

During this portion of the approach, the integrated electrical conductivities and acoustic parameters are related to physical properties such as pore structure and matrix material. This is a difficult procedure since the microscopic properties under consideration are heterogeneous and a general technique to project this complex information onto an integrated measure of conductivity over a representative volume is required. The information, which is provided by in situ measurements and laboratory analysis of core samples, is used to develop a model that predicts the observed macro-scale conductivity distributions. The model is then tested over additional material and updated to reflect the new information. A few methods that may be applicable to this model building task are summarized in the next section.

IV. DEFINE POSSIBLE METHODOLOGIES OR MODEL BUILDING SCHEMES TO ADEQUATELY RELATE CONDUCTIVITY TO MATERIAL TYPE

Model development for electromagnetic classification problems are composed of two parts. The first part of the problem is associated with the inversion of the data to obtain conductivity distributions within the sediment. Once conductivity distributions are obtained, the identification of an accurate composite representation for the physical properties such as porosity, permeability and matrix/fluid chemistry within the volume investigated is the most important component of the model building effort. Several possible approaches are summarized below.

IV.1 Random Media Models

The selection of specific methodologies that are most

appropriate to map the complex microscopic material fabric and mineral constituents into a representative elementary volume with well defined statistical moments should be an important component of the research effort. Random or embedded (nested) networks based on appropriate scaling laws may be candidate models (Madden, 1976). Extensive work on the use of percolation theory (Stauffer, 1985) and random walk (Schwartz, et al., 1983) approaches have been implemented to describe mass transport in fractured or porous media. Since the same physical properties which control fluid transport in sediments have a major impact on electrical properties, the statistical schemes derived for mass transport may be appropriate to define bulk electrical measures.

IV.2 Effective Moduli Models of Composite Material

From the material science community considerable emphasis has directed to understanding the macroscopic properties such as elastic or dielectric characteristics of complex composite materials. The basic problem is to derive the governing field equations for a macroscopic region using knowledge on the basic properties of the material's microscopic constituents. In other words, this is an example for estimating the effective moduli of a media from poorly defined micro-scale properties and results in an incompletely posed inverse problem. A mathematical technique, which has been developed to address this problem through the study of the governing partial differential equations and boundary conditions, is homogenization theory (Ericksen, et al., 1986). Since the constitutive properties of the marine sediments are quite variable and poorly defined, the problem of estimating bulk geophysical moduli in this case is a much more complex problem than those considered in the material sciences area. However, there are clear relations between electrical conductivity and acoustic wave propagation in ideal cases (Brown, 1980). Perhaps this formalism may be adapted to provide means of relating both electrical and acoustic parameters in a synergistic way to the microscopic properties of marine sediments.

IV.3 Frequency Dependent Empirical Power Law Models

Over the last thirty years a large amount of research has been conducted in the field of electrochemistry associated with induced polarization (IP). This phenomenon has been utilized for mineral prospecting and for mapping environmental contaminates in terrestrial settings over the intervening years. Reservoir engineering in the petroleum industry has pioneered the development of power law relationships between conductivity and porosity (Archie, 1942). Recently investigators have incorporated frequency dependent terms into the power law models. These terms account for the IP response caused by formations containing clays or other material with high cation exchange capacities (Park and Dickey, 1990;

Vinegar and Waxman, 1984). These improved power law relaxation models may be appropriate for marine applications.

V. APPROXIMATIONS REQUIRED TO INVERT MACRO-SCALE MEASUREMENTS FOR CRITICAL PARAMETERS

There are two fundamental approximations required to solve the characterization problem using non-invasive geophysical measurements.

The first and most commonly acknowledged issue is associated with the problem of solving for the unknown constitutive parameters such as conductivity, density or acoustic velocities from electromagnetic and acoustic measurements acquired over a limited spatial and temporal (frequency) range. In most geophysical problems, this procedure is mathematically ill-posed. In other words, any uncertainty in the measurements will translate into very large errors in the estimation of the desired parameters. The solution to this problem has been implemented through the use of a vast number of mathematical techniques commonly lumped under the title of inverse theory (Menke, 1984; Tarantola, 1987).

The second fundamental approximation that must be made is related to process of mapping a very complex microscopic fabric of physical or material properties into a macroscopic model. This macroscopic model must provide a representative picture of the aggregate constituents throughout the volume, which is defined by the spatial resolution of the geophysical technique that was used to examine the media. This is an extremely important step in the interpretation process and is responsible for transmitting all relevant information about the physics of the media into a simplified but quantitative representation of the composite material.

V.1 Approximations Associated with the Inversion of Geophysical Data

A major difficulty associated with the utilization of indirect or remote measurements to quantify a physical parameter is associated with the implementation of a stable or robust inversion scheme that accepts noisy geophysical data. To realize this goal, some form of smoothing or regularization must be incorporated into the process. This procedure limits the inferred parameters to a small subset of all possible solutions (Tikhonov and Arsenin, 1977). This lack of uniqueness of the solution has major implications on the validity of the interpretations. However, the utilization of multiple techniques to measure related physical properties has the advantage of providing more robust solutions than the separate interpretation of each technique (Vozoff and Jupp, 1975). This synergism provides an important means to constrain the solution with the addition unbiased information. An example of this would be to use both electromagnetic and

acoustic data to infer sediment porosity. The specific regularization scheme that is used to interpret any data is in fact the basic approximation used in the model building effort. Each type of remote and even in situ electrical measurements will have this smoothing operator superimposed on its inherent averaging kernel and will thus provide an integrated view of the true parameter distribution.

V.2 Approximations Associated with Mapping Microscopic Properties and Processes into an Integrated Macroscopic Representation

The problem of defining a macroscopic model that accurately reflects the microscopic structure, chemistry and dynamics of a porous sedimentary material is probably one of the most challenging problems for researchers to address in the field of coastal marine sciences. Since the bulk electrical conductivity is a function of the pore structure, matrix composition and interstitial fluid chemistry, a quantitative understanding of not only the sediments but also the associated equations that define multiphase dynamics in a continua are required. An important property of any sedimentary material is the porosity, which affects not only the electromagnetic and acoustic responses but also has a major influence on the fluid flow or mass transport through the media. In the case of fluid flow, fluid dynamic specialists have long been interested in the problem of *transient loading* of porous media and a formalism known as Mixture Theory has been developed to deal with this issue (Mei, 1989). This formalism provides the governing equations for multiphase dynamics that is currently an active area of research in soil mechanics. Since solutions that include nonlinear behavior and general three dimension distributions of constituent parameters are difficult achieve, simplified or approximate realizations are used to address specific classes of problems. An analogous problem would be the solution of Maxwell's equations in a realistic three dimensional conductivity distribution. These are extremely difficult forward problems and simplifying assumptions about the heterogeneous nature of the microscopic properties at some scale are required. Several methodologies to define these representative elementary volumes were summarized in the previous section. The obvious multi-disciplinary nature of the problem and the broad scope of the research issues requires the skills of geophysicists, geochemists, marine geologists, biologists, mathematicians, material scientists and fluid dynamists to name a few.

VI. VERIFICATION OF INTERPRETATION PROCEDURES

Verification of the interpretation schemes used can only be implemented through a combination of direct observations, chemical analysis and small scale indirect measures over a suite of parameter values. Remote sensing data must then be

acquired over these areas and inferred parameter values must be compared to the "true" parameters defined by in situ and laboratory tests. This must be an iterative process with improved models evolving as interpretation constraints are amended.

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A 5-year Special Research Program (SRP) has been established at the Naval Research Laboratory that addresses the physical characterization and modeling of benthic boundary layer processes and the subsequent impact of these processes on the seafloor properties that affect mine countermeasure operations. This special project outlines the SRP scientific program and reviews the results of the four workshops convened to establish scientific priorities. Workshop participants agreed that sediment structure provides the common perspective: to quantitatively model relationships among sediment physical properties; to quantify the effects of environmental processes on sediment properties; and to model sediment behavior (acoustic, electrical, and mechanical). Hypotheses based on quantitative physical models that incorporate three-dimensional sediment structure will be tested by a series of field experiments at coastal locations where differing environmental processes dominate sediment structure. These experiments stress the role of sediment structure in determining high-frequency acoustic phenomena such as scattering, penetration, and propagation, as well as the physical relationships between remotely sensed acoustic properties and mechanical strength parameters.

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